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MEASUREMENT COMPONENT TECHNOLOGY

CRYOGENIC TEMPERATURE MEASUREMENT AND HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

FINAL REPORT

13 OCTOBER 1972

VOLUME III

Contract NAS7-200

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Task Manager
Launch Vehicles Engineering

Space Division
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102

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FOREWORD

This report documents the work performed by North American Rockwell Corporation through its Space Division in fulfillment of a Task Authorization entitled, "Measurement Component Technology," sponsored by the National Aeronautics and Space Administration's George C. Marshall Space Flight Center, Huntsville, Alabama, under contract NAS7-200 in accordance with Task Authorization 2026-TA-36. The work was performed by members of the Electrical and Electronics Systems branch of the Space Systems and Applications Division during the period July 12, 1971 through October 13, 1972. NASA technical monitors were Messr . W. T. Escue, S&E-ASTR-IM, H. S. Herman and R. C. Holder, S&E-ASTR-IMP, J. F. Hamlet, S&E-ASTR-IMP and J. E. Zimmerman, S&E-ASTR-IMT.

The report consists of three volumes, of which this is Volume III. Volume numbers, document numbers and volume titles are listed below.

Volume I - Cryogenic Pressure Measurement Technology and Subjects Allied to Pressure Transducers. Document Number SD72-SA-0156-1.

Volume II - Liquid Detection Measurement Technology and Cryogenic Flow Measurement Technology. Document Number SD72-SA-0156-2.

Volume III - Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology. Document Number SD72-SA-0156-3.

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TECHNICAL REPORT INDEX ABSTRACT

UNCLASSIFIED

CRYOGENIC TEMPERATURE MEASUREMENT AND HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

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TRANSDUCERS
FLOWMETERS
PRESSURE TRANSDUCERS
STRAIN GAGES
FLANGE SEALS
HYDROGEN EMBRITTLEMENT
TEMPERATURE TRANSDUCERS
LIQUID DETECTION TRANSDUCERS

THIS REPORT DOCUMENTS THE RESULTS OF AN INVESTIGATION INTO THE AVAILABILITY AND PERFORMANCE CAPABILITY OF MEASUREMENT COMPONENTS IN THE AREA OF CRYOGENIC TEMPERATURE, PRESSURE, FLOW AND LIQUID DETECTION COMPONENTS AND HIGH TEMPERATURE STRAIN GAGES. IN ADDITION, TECHNICAL SUBJECTS ALLIED TO THE COMPONENTS WERE RESEARCHED AND DISCUSSED. THESE SELECTED AREAS OF INVESTIGATION WERE: (1) HIGH PRESSURE FLANGE SEALS, (2) HYDROGEN EMBRITTLEMENT OF PRESSURE TRANSDUCER DIAPHRAGMS, (3) THE EFFECTS OF CLOSE-COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENT, (4) TEMPERATURE TRANSDUCER CONFIGURATION EFFECTS ON MEASUREMENTS, AND (5) TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS.

THE PURPOSE OF THE PROGRAM WAS TO INVESTIGATE THE LATEST DESIGN AND APPLICATION TECHNIQUES IN MEASUREMENT COMPONENT TECHNOLOGY AND TO DOCUMENT THIS INFORMATION ALONG WITH RECOMMENDATIONS FOR UPGRADING MEASUREMENT COMPONENT DESIGNS FOR FUTURE S-II DERIVATIVE APPLICATIONS. RECOMMENDATIONS ARE PROVIDED FOR UPGRADING EXISTING STATE-OF-THE-ART IN COMPONENT DESIGN, WHERE REQUIRED, TO SATISFY PERFORMANCE REQUIREMENTS OF S-II DERIVATIVE VEHICLES.

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CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

As space missions become more complex and more demanding, the requirements on measurements grow more and more difficult. Constant improvements in measurement techniques and accuracy are being sought by design engineers for a more accurate evaluation of system performances. Ever increasing severity in operating environments requires a continued search for new designs and techniques.

Greater reliability of equipment is required as space missions grow more complex. Lower component weight, smaller size and lower electrical power consumption are sought as mission duration grows longer. All of these factors and many more require that measurement capabilities be upgraded to meet these new demands. The purpose of this study is to satisfy some aspects of this need with an investigation into measurement component technology.

S-II derivative systems, including the Space Tug, Orbiting Propellant Depot (OPD), Expendable Second Stage (ESS), and Chemical Interorbital Shuttle (CIS) impose many new performance requirements on measurement components not currently required by the S-II stage or the Saturn V vehicle.

Higher measurement accuracy, long term operation in high and low temperature environments, repeated operations in relatively high vibration environments, long term shelf life and repeated reuses are some of the more important performance requirements. Light weight, small package size, simplified wiring requirements, low electrical power, and simplified maintenance procedures are other desirable characteristics for future space vehicles.

This program investigated the availability and performance capability of specific measurement components in the area of cryogenic temperature, pressure, flow and liquid detection components and high temperature strain gages. The study conducted a systematic survey of manufacturers to establish performance and physical characteristics of current designs. In cases where current state-of-the-art equipment cannot meet performance requirements for future space missions, the design shortcomings are identified and recommendations for improvements, where available, were presented and discussed. The study evaluated published information and supplier furnished data and discussed some advantages and disadvantages for given designs. Measurement system application design considerations were investigated and discussed in the report where these considerations were an important part of the measurement. The results of the investigation were intended to provide a useful reference source for design and component information for the selection and application of the measurement transducers of this investigation.

In addition, specific technical topics allied to the measurement type or components were researched and are discussed in this report. Items selected for investigation as part of this study were selected for the problem nature of the item or for the technical value of the researched information as a reference source for new designs. Selected areas for investigation were (1) high pressure flange seals, and (2) hydrogen embrittlement of pressure

transducer materials. Other topics which involve application were (1) the effects of close-coupled versus remote transducer installation on pressure measurements, (2) temperature transducer configuration effects on measurements, and (3) techniques in temperature compensation of close-coupled strain gage pressure transducers.

These specific measurement component capabilities and technical topics are contained in three volumes. Volume I contains Cryogenic Pressure Measurement Technology, High Pressure Flange Seals, Hydrogen Embrittlement of Pressure Transducer Materials, the Effect of Close-Coupled Versus Remote Transducer Installations on Pressure Measurements, and Techniques in Temperature Compensation of Strain Gage Pressure Transducers. Volume II consists of Cryogenic Flow Measurement Technology and Cryogenic Liquid Detection Measurement Technology. Volume III summarizes Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology.

CRYOGENIC PRESSURE MEASUREMENT TECHNOLOGY

The investigation into cryogenic pressure transducer technology was made by conducting a survey of manufacturers to establish transducer capability of currently available equipment. The requirement established for the search was to locate an instrument capable of operating with liquid oxygen or liquid hydrogen systems of a space vehicle while maintaining temperature sensitivity errors within 2 percent of full scale.

Since the investigation did not result in meeting this design goal, a literature research was conducted to identify problem areas which contribute to this transducer performance limitation.

This report presents the results of the industrial survey and the literature research.

HIGH PRESSURE FLANGE SEALS

Consideration of a high pressure (5000 psi) transducer for applications whose design concept utilized flanged mounting precipitated this investigation. The research work primarily addresses itself to the search for a metallic seal to attain optimum sealing for low temperature, high pressure systems. The investigation relied principally upon published literature as the source for information.

HYDROGEN EMBRITTLEMENT OF PRESSURE TRANSDUCER MATERIALS

The hydrogen embrittlement investigation utilized published literature for obtaining information on the susceptibility of transducer materials to the embrittlement problem. The investigation emphasized the practical approach by categorizing transducer metals with respect to embrittlement susceptibility. The investigation did not deal with the atomic structure or metallurgical aspects of metals.

THE EFFECTS OF CLOSE-COUPLED VERSUS REMOTE TRANSDUCER INSTALLATION ON PRESSURE MEASUREMENTS

A technical discussion on the effects of close-coupled versus remote transducer installation effects on measurement accuracy was presented in this report for reference information to transducer users. The discussion in the report was based on information derived from Saturn S-II flight tests and laboratory work performed in conjunction with investigations into the Saturn S-II low frequency oscillation phenomenon. Data distortion due to line length is illustrated and corrective methods are delineated.

TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE TRANSDUCERS

Another topic presented in the report is based on investigations of temperature sensitivity problems of strain gage pressure transducers. Since the Saturn S-II low frequency oscillation phenomenon resulted in utilizing close-coupled strain gage transducers on the LOX feedlines of engine 1 and 5, an investigation was made to establish techniques available for compensation of temperature sensitivity errors. This information is provided in this report as reference material.

CRYOGENIC MASS FLOW MEASUREMENT TECHNOLOGY

The flow investigation researched current technology for systems capable of cryogenic temperature flow measurements. Manufacturers were contacted for information on their product line of flowmeters which indicated promise of meeting an application requiring a mass gas flowmeter.

A hypothetical case for a cryogenic temperature gas flow measurement was established for the purpose of assessing whether any of the candidate systems would be acceptable for this case. The report provides the technical discussions resulting from this evaluation as well as descriptions of individual manufacturers systems.

CRYOGENIC LIQUID DETECTION MEASUREMENT TECHNOLOGY

The cryogenic liquid detection technology portion of this study was limited to an industrial survey. Manufacturers of positive and low gravity detection systems were contacted and their equipment and, in some cases, experimental concepts, are presented. The report describes each system including theory of operation, accuracy, stability, power requirements, and the gravitational environment in which the system is designed to perform.

CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

The investigation into cryogenic temperature transducer technology was made by conducting a survey of manufacturers to establish the capability of currently available equipment to meet cryogenic system requirements. In conjunction with this survey, a literature search was conducted to identify new developments in temperature measuring techniques. The methods of temperature measuring discussed are resistance temperature transducers made from different metals as sensing elements, thermistors, and thermocouples. Also included is a discussion of measuring bridges used to determine the resistance of the temperature probe.

HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

Although strain measuring techniques have progressed rapidly since the development of the first strain gage, the requirements for their use have advanced much faster. This is especially true for obtaining flight load measurements on high speed vehicles operating in the earth's atmosphere.

The aerodynamic heat associated with this high speed flight can be a major cause of strain gage error. Temperatures up to 1800 F are anticipated on the aerodynamic surfaces of a mach 6 vehicle operating at 90,000 feet. Strain gage output due to thermal stresses at these high temperatures can produce load measurement errors greater than those due to gage performance characteristics. To obtain accurate flight load measurements these errors must be eliminated in the strain gage design.

The purpose of this section of the components technology report is to review various strain sensing devices and evaluate their performance in a 1500 F to 2000 F thermal environment.

2.0 SUMMARY

The following is a brief review of the significant facts contained in the body of the three volume text. The summary is contained in each of the three volumes in order that the reader might have sufficient information to evaluate his need to review each volume's text in detail.

Volume I contains the following topics: Cryogenic Pressure Transducer Technology, High Pressure Flange Seals, Hydrogen Embrittlement of Transducer Materials, the Effect of Close-Coupled Versus Remote Transducer Installations on Pressure Transducers, and Techniques in Temperature Compensation of Strain Gage Pressure.

Volume II contains the following topics. Cryogenic Mass Flow Measurement Technology and Cryogenic Liquid Detection Technology.

Volume III contains two topics: Cryogenic Temperature Measurement Technology and High Temperature Strain Gage Technology.

CRYOGENIC PRESSURE TRANSDUCER TECHNOLOGY

Pressure measurements for space vehicle cryogenic systems such as for liquid oxygen and liquid hydrogen tanks, transfer lines and engine systems, have always presented a special challenge to instrumentation engineers and measurement users alike. These cryogenic liquids, especially liquid hydrogen, possess many properties which pose problems for designers. Primarily, these problems are associated with low temperature environments and with the highly volatile nature of the liquid. The most common approach to measuring pressure in these systems is to connect the pressure transducer away from the extreme low temperature environment by connecting the transducer to the sense port by a length of sense line which provides a thermal buffer for the transducer. This technique is satisfactory for only steady-state or slowly changing measurements. For oscillating or fast changing pressure systems the volatility of the liquid creates thermal dynamic oscillations and the sense line reduces frequency response both of which reduce measurement fidelity markedly.

This investigation was performed to research currently available designs which could be utilized for space vehicle applications in cryogenic systems to an accuracy of 2 percent excluding other environmental error sources.

Inquiries made to approximately 50 manufacturers resulted in seven favorable responses from suppliers indicating the availability of transducers operable with cryogenic systems of liquid oxygen or liquid hydrogen. Manufacturers responding favorably to the survey were:

Manufacturer	Transducer Type
Bell & Howell/Consolidated Electrodynamics	Unbonded Strain Gage
Bourns Inc.	Potentiometer
Dynasciences Corporation	Bonded Strain Gage
Genisco Technology Corp.	Bonded Strain Gage
Kistler Instrument Corp.	Piezoelectric
MB Electronics	Bonded Strain Gage
Statham Instruments Inc.	Deposited Strain Gage

A number of other manufacturers are known to have developed pressure transducers operable in cryogenic systems but these designs are available on special order only and thus were not included in this study primarily due to the lack of descriptive information on the instruments.

This investigation concluded that for the many application conditions of a space vehicle, none of the candidate instruments could meet the design goal of 2 percent temperature sensitivity error. Based on this conclusion, problems contributing to temperature sensitivity were investigated through research of published documents.

The single most important error source for instruments found by the researchers is the difference in temperature conditions between instrument calibration and the using temperature environment. Normally transducers are calibrated under a steady state, uniform temperature environment, usually at the liquid nitrogen temperatures. In field applications temperature gradients occur between the front face of the transducer to the aft end of the instrument. For transducers with temperature compensation provisions such as the strain gage designs, the compensation thermistors and resistors are located in the aft end of the instrument. This design alone contributes to a significant error found by one researcher to be as much as 100 percent FS for transducers that indicated less than 6 percent FS shift in standard steady state temperature tests.

A definite improvement in low temperature performance can be achieved on the part of instrument users by providing installation designs which minimize thermal gradients, such as by insulating the transducer, and by calibrating instruments under conditions of usage as closely as possible.

The conclusion of this investigation is that for applications requiring good temperature compensation, small size, low heat capacity and high frequency response with the capability of measuring both steady state and dynamic responses a new transducer design is required. Based on the information provided by researchers some design features known to provide desirable performance characteristics are: flush diaphragm design with diaphragm machines integral with the case, small case size with short body length and low thermal mass, strain gage design with gages mechanically coupled to the diaphragm in an unbonded configuration, temperature compensation circuitry located in the same thermal environment as the strain gages and transducer installation provisions which facilitate insulation provisions to minimize thermal gradients.

HIGH PRESSURE FLANGE SEALS

This investigation primarily addresses itself to the search for a metallic seal for cryogenic temperature and up to 5000 psig pressure applications.

The leakage rate for a seal depends on fluid properties, surface topography, pressure differential, hardness of the sealing material, and sealing contact stress.

The most important design considerations are pressure, temperature range, and type of fluid sealed. These parameters determine the bolt size, flange thickness, and materials.

Leakage is the most important criterion and most difficult to predict without tests. Many metal seals are capable of achieving leakage rates below measurable levels; however, the penalty in flange loading, extremely smooth finishes or loss of recovery, may be prohibitive. For extremely low leakage rates (less than 10^{-8} scc/sec), an all-metal seal is usually required.

Seating load is an important parameter in flanged connections. The lower it is, the smaller the required flanges and bolting. Seating load is normally expressed in pounds per inch (lb/in) of seal circumference and may range from 100 to 500 lb/in, depending on the design.

Contact stress at the sealing interface partially determines leakage rate and is a function of seating load and contact area. The pressure differential across the interface, if high enough, may add or subtract significantly from the initial contact stress.

Metal seals capable of very low leakage rates must plastically deform at the sealing interface. With subsequent installations, the seal coating must try to conform to a new set of peaks and valleys and intimacy of interface is consequently reduced.

Pressure compensation, sometimes called pressure energization, pressure actuation, or pressure assistance, is the beneficial effect of pressure upon the seal contact. The geometry of many seals is such that fluid pressure augments the contact stress, thus tending to overcome the increased possibility of leakage due to the pressure. The pressure effect is negligible except at high pressures - 1000 psi or more.

Cavity requirements of the seal must provide for correct (limited) deflection of the seal, location of the seal, structural support for high pressure, and proper surface finish.

The choice of seal materials is usually determined by the operating temperature, although corrosion resistance, fluid compatibility, and radiation effects may also be major considerations. Most metal seals contain two materials, a resilient, basic-shape metal and a soft coating.

The coating material is usually a pure metal (silver, gold, nickel, or copper) or a plastic dispersion coating such as Teflon. Coating materials are chosen on the basis of softness, corrosion resistance, temperature resistance, and cost. Silver is used in the majority of low and high temperature applications and is one of the least costly.

Resilient metal seals combine the efficiency of elastomeric O-rings with the extended temperature capability of metal gaskets. The basic structural element is usually a high-strength metal, and a soft coating of metal or plastic provides the actual sealing. Like O-rings, these seals are self-energizing, have small cross sections, require light closing forces, are often reusable, and

have indefinite life. Unlike O-rings, however, they are relatively expensive, and availability is somewhat limited.

Resilient metal seals can be considered as the most promising for achieving seal integrity for high pressure and cryogenic environments. A parallel loaded joint with a groove type seal installation should provide the optimum joint configuration.

HYDROGEN EMBRITTLEMENT OF TRANSDUCER MATERIALS

The research work performed within the industry on hydrogen embrittlement of metals has not resulted in a clear definition of accepted standards. Because of this fact, no precise conclusions can be reached on the extent of hydrogen embrittlement as a problem for instrumentation systems. Primarily, this uncertainty results from the fact that most testing has been accomplished at 10,000 psi and pressures for liquid or gaseous hydrogen systems on Saturn S-II type vehicles are 100 psi to 1000 psi.

Generally, it is concluded that no problems exist for materials most often used for transducer construction. This conclusion is based on the experimental findings that embrittlement susceptibility increases with increasing temperature above room temperature and increasing pressure. Below room temperature embrittlement susceptibility decreases with decreasing temperature. Hydrogen has little effect on metals below a temperature of -321 F. From the standpoint of instrumentation systems, this is favorable since the majority of measurements in hydrogen systems are made at low temperature and pressures.

The report summarizes the degree of susceptibility for various metals where data are available.

THE EFFECT OF CLOSE COUPLED VS. REMOTE TRANSDUCER INSTALLATIONS ON PRESSURE MEASUREMENTS

The measurement of frequency over a line length of constant diameter to which is attached a sensing transducer varies as the fundamental (fd) frequency. If the media transmitting the frequency is a gas, then the frequency is limited by the line length and the acoustic velocity. The exception to this is a situation in which the volume of the transducer cavity measuring the pressure pulse is large relative to the volume of the line. This case is called a Helmholtz resonator and it will produce an attenuation of approximately 40% over the previously noted fundamental frequency for the equivalent line length.

If frequency of pulsations of a liquid over a line is required and if the liquid is a cryogenic, a multitude of problems arise. Pressure pulses of large amplitude will produce complete distortion of phase, frequency, amplitude and signature. Small pressure pulsations will allow the passage of phase and amplitude data within the fundamental frequency range but amplitude and signature cannot be considered correct. The turbulence produced by the

pressure pulsations forces the liquid down a gas filled line where it expands due to the sudden temperature gradient. The resultant change in momentum of the mass of cryogenic liquid in motion and the volume change produces an overall distortion of the output.

The accurate measurement of [illegible]ality of a cryogenic liquid can only be obtained by using either a close coupled or flush mounted transducer. The ideal installation is that of mounting a pressure transducer diaphragm directly against the media to be measured. If this is not possible then the sensor can be boss mounted off a fitting. Care must be taken in the last instance in that a short run from the liquid to the sensor diaphragm might form a Helmholtz resonator.

TECHNIQUES IN TEMPERATURE COMPENSATION OF STRAIN GAGE PRESSURE

The classic techniques for compensation of pressure transducers to temperature sensitivity is to select materials with desirable performance characteristics and to apply compensating resistors and thermistors to the bridge circuitry. These techniques compensate for zero shift and sensitivity changes.

Manufacturers can further improve transducer performance by locating the resistors and thermistors in the same thermal environment as the temperature sensitive member. Instrument users can insulate instruments to stabilize temperature and can apply corrections to calibration curves for zero shifts determined from a reference pressure test.

CRYOGENIC MASS FLOW MEASUREMENT TECHNOLOGY

The object of the cryogenic flow study was to establish the state-of-the-art and to recommend either a specific flow system or if that was not possible, to establish a direction for future development.

The measurement of cryogenic mass gas flow depends upon the determination of several variables. If the measurement is made either inferentially or directly, a compensation of variables must be taken into consideration. Density is always common to an inferentially mass measurement with either a velocity or velocity squared measurement required. Since density itself can be a function of pressure, temperature, torque or damping ratio an inferential measurement of flow can consist of a great deal of variables; some of which can cover a large range. In the direct measurement of mass flow the output can be a measurement of linear or angular momentum or heat transfer. Although the output can be a single variable the mechanism required to generate the output can be extremely complex and limited in range. In addition to the above noted problems, there are a number of material, installation and design problems that also must be solved.

The initial 62 manufacturers reviewed were reduced to 16 candidate systems. These candidate systems consisted six true mass flow meters and eleven inferential mass meter systems. In addition to manufacturers of flowmeters, such associated problems as facility calibration and previous

data were reviewed. After analyzing all candidate systems, previously run test data, test facilities and the National Bureau of Standards at Boulder, it was concluded that no flowmeter had a proven history of meeting the requirements. Two system types looked promising — the turbine-capacitance densitometer inferential meter and the heat transfer mass momentum meter. Of these two systems, only the inferential turbine candidate had some data at a cryogenic gas temperature and hence is the recommended choice.

CRYOGENIC LIQUID DETECTION TECHNOLOGY

This section covered twelve propellant gaging systems offered by nine manufacturers. Five of the systems are applicable to positive g applications and seven are applicable to both positive and zero g usage. These systems can be further categorized into five basic operating principles. These are point sensor, capacitance probe, radio frequency, infrasonic, and nucleonic systems. Point sensors and capacitance probes are only useful in positive g environments. The infrasonic and nucleonic systems are applicable in zero g environments, however, both designs are still in the development stage and at this time impose a high weight penalty to obtain good accuracy.

The use of the more standard coaxial cylinder capacitance sensor system for continuous gaging of propellants is not practical due to the capillary rise that occurs at low gravity conditions. The capillary rise for LH_2 and LOX is on the order of 40 and 20 inches respectively for capacitance sensors similar to those used in the Saturn S-II stage.

Since future space vehicles operate under both zero g and positive g environments, no single concept of propellant gaging provides the desired accuracy under both conditions. The results of the study indicate that the radio frequency system is best for propellant monitoring during zero gravity periods when propellant tanks are less than half full. During periods of positive g the discrete level sensing system offers the best accuracy especially during propellant loading and for monitoring the liquid level with tanks full. The best design compromise appears to be a system utilizing both the RF system and discrete level sensors for all phases of the vehicle operation.

CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

Commercial cryogenic thermometers are available which are capable, under carefully controlled conditions, of precisions greater than $\pm$ 0.05 K. However, such precision can only be obtained under static or quiescent conditions. When thermometers are required to respond to rapid temperature fluctuations such as occur in the cooldown of propellant lines, the indicated temperature may depart significantly from the "true" temperature. The loss in validity of the measurement does not reflect a degradation in accuracy of the temperature sensor, but rather indicates that the temperature of the sensor is not at all times the same as the surroundings.

The terms "accuracy" and "reproducibility" require some explanation pertaining to temperature transducers. Accuracy is the significance with which the thermometer can indicate the absolute thermodynamic temperature. This includes errors of calibration as well as errors due to nonreproducibility. Reproducibility is the variability observed in repeating a given measurement using

ifferent thermometers of the same type. Changes produced by thermal cycling of the thermometer to and from ambient are also included in this parameter.

Temperature sensor materials can be divided into three categories: pure metals, non-metals, and thermoelectric devices called thermocouples. While there exist a number of pure metals that are more or less suitable for resistance thermometry, platinum, primarily because of many favorable characteristics, has become predominant as a temperature measuring element. Desirable features such as ready availability in high purity and extensive knowledge about platinum's behavior down to 20 K have tended to perpetuate its use. Its principal disadvantages are low resistivity and insensitivity below about 10 K.

Copper, nickel and tungsten have also been exploited as temperature sensing elements. Copper is inexpensive and has a very linear temperature/resistance relationship. Copper has poorer stability and reproducibility than platinum and its low resistivity is undesirable when a high resistance element is required for temperature measurements below 100 K. Nickel is widely used over the temperature range of 170 K to 575 K; however, this report was primarily concerned with temperatures below 100 K and at this temperature, very little work has been done with nickel. Tungsten sensors are less stable than other metal sensors because full annealing is impractical. At low temperatures the percentage change in resistance per degree is much less than platinum. Tungsten's great mechanical strength allows extremely fine wires resulting convenience for manufacturing sensors having high resistance values, but this is not important unless the probe resistance must be larger than 5 or 6 thousand ohms.

Non-metals such as semiconductors, carbon resistors, and thermistors are used as temperature sensing devices in the laboratory with some advantages over pure metals. The greater disadvantages for their usage on a space vehicle within the temperature range of 20 to 100 K tend to discount them as a serious consideration unless further development and knowledge is pursued.

Germanium semiconductors are available from several commercial sources. The sensing element is a small single crystal with high resistivity. The resistance/temperature relationship is very complex and requires many calibration points when used over a wide temperature range. The reproducibility is poor and thermal cycling causes some drift to occur. This affects their interchangeability drastically.

Carbon resistors have been used as temperature sensors at extremely low temperatures. Carbon has a high sensitivity in the temperature range of 0.1 K to about 20 K; however, above 20 K the dR/dT is very unstable.

Thermistors are inexpensive and very sensitive to temperature. They are small in size and have a high resistivity. Thermistors have a nonlinear R-T relationship and poor stability. Because of the nonlinearity, numerous calibration points are required. A single thermistor is generally unsuited for wide temperature spans because its resistance goes from values which are so high to be inconvenient to values which are too low to be measured with conventional signal conditioning equipment. Several thermistors must be used to cover a wide temperature span.

Thermocouples in comparison with other temperature sensors have certain advantages. The temperature sensitivity span can be small, and is more flexible for installation. The thermocouple is a device of comparatively low cost, high accuracy, wide measurement range, fast thermal response, ruggedness, and reliability. Some of the more obvious disadvantages are the very low output voltage requiring more complex and costly signal conditioning equipment, and the homogeneity of the materials used to manufacture thermocouples is such that interchangeability without complete recalibration is impractical.

After an objective analysis of the different methods of temperature measurement in the 20 to 100 K range, the wire wound metal, especially platinum, is best suited for measurements where high accuracy and stability is required. The thermistor is best for point measurements and the thermocouple best for high temperatures or for rough indication of temperatures.

Resistance bridges are used as a comparison device for measuring precise resistance ratio relative to temperature change of a platinum thermometer. In making comparison resistance measurements for attainment of a high degree of precision, of the order of 1.0 PPM, the following design considerations should be evaluated when selecting a particular bridge design: effects of lead resistance, thermoelectric emf's, self-heating, reactance, bridge linearity, noise, interaction, bridge sensitivity, and accuracy.

From the numerous available bridge designs, a designer has to determine as to which of the bridge designs is most suitable for use for a particular design application. Therefore, in order to establish a methodical design approach, these numerous bridges are described in its basic form as either a full or half bridge. These basic bridges are then evaluated for its advantages and disadvantages based on applicable design considerations. In the process of evaluation, these basic bridges are reconfigured for use as either symmetric or asymmetric configuration and as a low level or high level bridge output based on the importance of a particular design consideration. A table depicting the advantages and disadvantages relative to the various design considerations has been prepared to provide direction in the design approach.

Lead resistance is widely accepted as a major problem in a temperature measurement system design. Because of this problem, numerous bridges such as Mueller, Smith, Seimens and numerous others have been developed since 1871. Each bridge has merits in leadwire resistance compensation, and therefore each is discussed in this report. Variations used in these bridges can then be adapted to the basic bridge selected for the best lead resistance compensation.

HIGH TEMPERATURE STRAIN GAGE TECHNOLOGY

The objective of this section of the components technology report was to review current strain sensing devices and evaluate their performance in a 1500 F to 2000 F airborne thermal environment. The evaluation consists of comparing gage principles of operation, gage materials, gage attach methods, installation techniques, performance characteristics and gage availability.

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A literature survey was conducted which resulted in the selection of three strain sensing devices for evaluation:

a. Electrical resistance strain gage

b. Electrical capacitance strain gage

c. Thermal-null strain sensor

The resistance strain gage operates on the principle that when a load is applied on any material, that material will expand or contract causing strain within the material. If a grid of wire is bonded to the material, it will stretch or be strained exactly as the surface of the test material is strained. This stretching and compressing of the grid wire causes a change in the electrical resistance of the wire which is proportional to the strain in the test member.

One of the major contributors to errors in high temperature strain gage applications is the effects of apparent strain. In a resistance gage, apparent strain causes a change in resistance of a mounted gage due to a change in temperature without an applied load on the test specimen. In an effort to reduce this apparent strain error, temperature compensation is included in the gage designs.

Many resistance gage alloys have been tested in an effort to extend the upper temperature limits. Most alloys exhibit a solid solution phase change below 1200 F. This phase change causes an anomaly in the resistance vs. temperature curve and yields an unsatisfactory alloy for high temperature strain gage usage. Platinum-tungsten alloys are currently the best available for high temperature resistance strain gages.

Attachment of high temperature resistance strain gages can be accomplished by using ceramic cement, aluminum oxide flame spray or by welding. The method used depends upon the material of the test specimen.

There are many resistance gages on the market today. However, only a relative few advertise the capability of operating at 1500 F and none at 2000 F.

Since 1968, Hughes Aircraft, and Wright Patterson Air Force Flight Dynamics Laboratory have coordinated on the development of a high temperature capacitance strain gage. This gage operates on the principle that variations in the gage dimensions caused by strain in the test specimen will change the capacitance of the gage. This change in capacitance is then directly proportional to the strain in the test specimen. The configuration selected for the capacitance gage was a parallel plate gage mounted in a rhombic frame. The gage consisted of a capacitance waffer containing stainless steel plates with mica dielectric insulators mounted in a stainless steel rhombic stress frame.

3.0 CRYOGENIC TEMPERATURE MEASUREMENT TECHNOLOGY

3.1 INTRODUCTION

Cryogenic temperature measurements are among the most numerous and important measurements on space vehicles containing cryogenic liquid propellant. Typical measurements required are for engine system performance evaluations, propellant conditioning data, tank and feedline insulation performance, propellant quantity and loading data, liquid-gas detection and stratification data. The highly volatile nature of liquid hydrogen and liquid oxygen make it mandatory for safety considerations that temperature measurements be accurate and reliable.

Temperature measurements fundamentally give information regarding the energy level or thermal potential of a substance. A temperature history indicates whether the energy level of a substance is increasing, decreasing, or remaining constant. However, the temperature that a sensor actually senses may be quite different from the temperature you want to measure. Proper choice of a temperature sensing device depends primarily on the following considerations: range, accuracy, and installation.

The temperature range of a measurement, in many cases, can immediately identify the kind of sensor needed. For example, if the temperature range is 1000 to 3000 F, the choice of a sensor narrows to either of several types of commercially available thermocouples. However, if the temperature range is -350 to -100 F, the choice widens to include several types of thermocouples, resistance thermometers, thermistors or even semiconductors. Accuracy requirements impose additional restrictions. Two factors must be reviewed. The first is the inherent accuracy of the measuring device. This includes repeatability and stability, and represents the best accuracy that can be achieved under ideal conditions. The second factor, usually more important, is the inaccuracy of the actual measurement caused by environmental effects, method of installation and use.

Future space vehicles require measurement accuracies of 1 to 2 percent of full range for many measurements. These accuracy values require that extreme care be exercised in the measurement system design, selection, and application of transducers.

This investigation was concerned with temperature region between 20 K and 100 K which encompasses the liquid temperature of oxygen, nitrogen, and hydrogen. These three fluids are most commonly used in space vehicle applications for propellants and pressurization.

Most cryogenic temperature measurements today are made by utilizing platinum resistance thermometers, and thermocouples. However, recent progress enlightens us on the possibility of using other sensors such as carbon resistance thermometers, thermistors, and semiconductors.

This report investigated each of the above mentioned types weighing the advantages, disadvantages, and application areas of each type versus the other. Also discussed is the role of resistance bridges in platinum wire resistance thermometry. However, design considerations discussed here may be useful relative to strain gage measurements and also to other types of temperature measuring sensors such as thermistors and other resistive type thermometers. The intent of this section is to establish a methodical approach to designing a resistance bridge associated with platinum wire thermometer for use on a medium to a large scale space vehicle.

3.2 TEMPERATURE MEASURING TECHNIQUES

3.2.1 Definition of Terms [1]

Accuracy - The ratio of the error to the full-scale output (usually expressed as "within ± ---- per cent of full scale output") or the ratio of the error to the output, expressed in percent.

Conduction Error - The error in a temperature transducer due to heat conduction between the sensing element and the mounting of the transducer.

Environmental Conditions - Specified external conditions (e.g., shock, vibration, temperature) to which a transducer may be exposed during shipping, storage, handling, and operation.

Error - The algebraic difference between the indicated value and the true value of the measurand, usually expressed in percent of the full scale output, sometimes expressed in percent of the output reading of the transducer.

Input Impedance - The impedance (presented to the excitation source) measured across the excitation terminals of a transducer.

Linearity - The error resulting from mechanical deformation of the transducer caused by mounting the transducer and making all measurand and electrical connections.

Range - The measurand values, over which a transducer is intended to measure, specified by their upper and lower limits.

Recovery Time - The time interval, after a specified overload, after which a transducer again performs within its specified tolerances.

Repeatability - The ability of a transducer to reproduce output readings when the same measurand value is applied to it repeatedly, under the same conditions, and in the same direction.

Resolution - The magnitude of output step changes (expressed in per cent of full scale output) as the measurand is continuously varied over the range.

Response Time - The length of time required for the output of a transducer to rise to a specified percentage of its final values as a result of a step change of measurand.

Self-Heating - Internal heating resulting from electrical energy dissipated within the transducer.

Sensing Element - That part of the transducer which responds directly to the measurand.

Sensitivity - The ratio of the change in transducer output to a change in the value of the measurand.

Stability - The ability of a transducer to retain its performance throughout its specified operating life and storage life.

Strain Error - The error resulting from a strain imposed on a surface to which the transducer is mounted.

Thermal Coefficient of Resistance - The relative change in resistance of a conductor or semiconductor per unit change in temperature over a stated range of temperature expressed in ohms per ohm per degree F or C.

3.2.2 Metals

The electrical resistance of pure metals varies with temperature from about 0.3 to 0.6 percent resistance change per degree K (Kelvin) at room temperature. Metallic sensors referred to as resistance temperature transducers (RTT) are most commonly platinum and nickel; however, copper, tungsten and nickel-alloy sensors are also used.

Materials used for the resistance elements are chosen on the basis of their:

a. Temperature Coefficient of Resistance

The sensitivity of the transducer is a function of the temperature coefficient of resistance or the change in resistance for a unit change in temperature. The higher the coefficient of resistance, the larger the resistance change for a given temperature span and the more sensitive the transducer. The normal range of values for the K factor (a measure of the temperature coefficient) is from 0.002 to 0.0035 ohms/ohm/F for conductor materials used as resistance thermometers. This equates to a resistance change of about 0.3 to 0.6 percent per degree centigrade or Kelvin.

The k factor is defined by the equation:

$$K = \left(\frac{R}{R_o} - 1\right) \Big/ \Delta T$$

Here, R_o is the resistance of the element at some convenient temperature, normally 20 C, T the temperature deviation from 20 C, and R the net resistance at the calculated temperature. This equation holds reasonably well over large temperature changes.

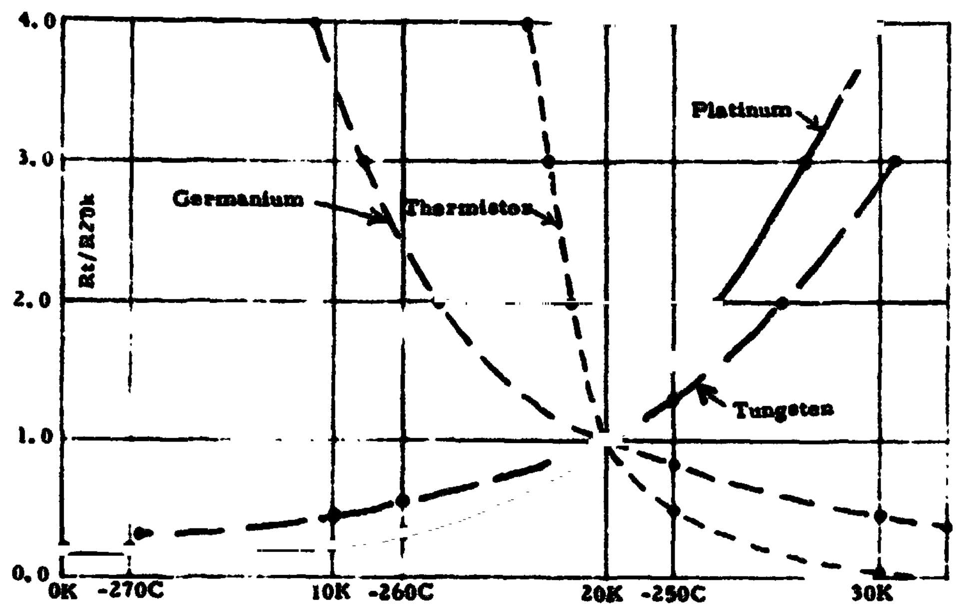


Figure 3.2.2-1. **Resistance/Temperature Relationship Low Range**

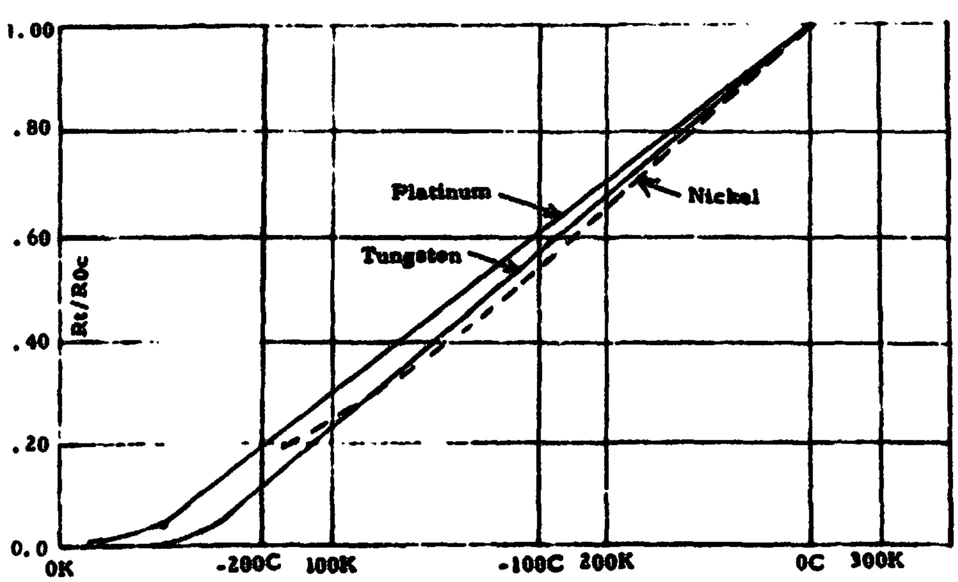


Figure 3.2.2-2. **Resistance/Temperature Relationship Medium Range**

Figure 3.2.2-1 compares various resistance type temperature sensors over the range of 0 K to 35 K fixing R_0 at 20 K. Figure 3.2.2-2 expands this relationship up over the medium range of temperature fixing R_0 at 273 K (0 C).

b. Resistivity

As with the coefficient of resistance the higher the element resistance the more convenient it is for measurement purposes. Total element resistance is related to the resistivity of the material and minimum diameter that the wire may be drawn which in turn is a function number of factors such as tensile strength and ductility.

c. Tensile Strength and Ductility

Both these factors determine the wire diameter for a given application and minimum wire size available. Platinum and many other materials are available in 0.007 inch diameter while tungsten with its high tensile strength is available in much finer wire diameters, down to 0.0002 inch.

d. Stability

For the transducer to be useful in a large number of applications, it must be stable under a wide variety of environmental conditions such as vibration and shock and in the presence of chemically active fluids. In addition, it must be chemically and metallurgically stable over long time periods.

e. Linearity

This characteristic is also desirable in that it simplifies the relationship between resistance and temperature, easing calibration and scaling as well as eliminating, in very linear transducers, a number of second order electrical problems.

Table 3.2.2-1 summarizes the properties of various conductors which have been used as elements in resistance temperature transducers. Included in the data presented are the resistance at 273 K in ohms per circular mil foot, the temperature coefficient of resistance in ohm/ohm/K, the approximate maximum a temperature of the base wire, the tensile strength, melting point and minimum wire size available.

Table 3.2.2-1 Characteristics of Common Temperature Probe Materials [3]

Material	Composition	Res. 273K (0C) ohms/cm.	R/R/K x 1000	Tensile St. 1000 lb/sq in	Min. Wid. Dia mils
Platinum	*C.P. (99.999%)	59.1	3.92	50-100	0.70
Tungsten	C.P.	30.3	4.50	400-500	0.14
Nickel	C.P.	36.0	5.22	120-150	1.50

*Chemically Pure

3.2.2.1 Platinum

The fundamental method of measuring temperature is the gas thermometer using thermodynamic principles. Although the gas thermometer is the accepted standard, it has limitations which prevent its practical use except in laboratories. To meet the need for a practical means of temperature measurement, the IPTS (International Practical Temperature Scale) evolved beginning in 1927 and finally agreed upon in 1958.

Over the range from the boiling point of liquid oxygen 90 K (-183 C) to the freezing point of Antimony 903 K (630 C), the platinum resistance temperature transducer is the internationally accepted practical means for temperature measurement in accordance with the IPTS. The Callendar-Van Dusen equation is the specified means for interpolating between fixed points.

$$T = \frac{1}{a}\left(\frac{R_T}{R_0} - 1\right) + \delta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) + \beta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right)^3$$

T = Temperature in degrees C

R_T = Resistance of thermometer

R_0 = Resistance at 0 C

a, δ, β Are imperical constants explained in later paragraphs.

Solving the equation for R_T/R_0 yields a useful form of the Callendar-Van Dusen equation as follows

$$\frac{R_T}{R_0} = 1 + a\left[T - \delta\left(\frac{T}{100}\right)\left(\frac{T}{100} - 1\right) - \beta\left(\frac{T}{100}\right)^3\left(\frac{T}{100} - 1\right)\right]$$

The constant β is measured at the oxygen point and is approximately 0.111 for temperature below 0 C. β is zero above 0 C.

Interpretation of a (alpha)

The magnitude of alpha is related to the degree of purity of the platinum wire and the degree to which it is free from strain. The addition of impurities to the wire causes alpha to decrease whereas mechanical contraints and strain may either increase or decrease alpha. Strain free wire of highest purity will have an alpha less than 0.03937 ohms/ohm/K. Most transducers used in aerospace applications have an alpha exceeding 0.003910 and approaching 0.003920.

Interpretation of δ (delta)

Above 273 K (0 C), the constant δ accounts for the nonlinearity of the resistance temperature characteristic curve. If δ were zero, then the curve would be a straight line with slope, a. The larger the value of δ, the greater the nonlinearity. Practically, δ is approximately equal to 1.49 and is positive.

Thus, the resistance temperature characteristic is almost a straight line and the negative second order term causes the curve to be concave downward.

3.2.2.2 Nickel

Nickel has been satisfactorily used as a resistance thermometer material. Its low cost as compared with the standard platinum thermometer has been the determining factor in its adoption for industrial measurement in the range from about -75 C to +150 C (-100 F to +300 F). Nickel is less stable than platinum, however, and has a much larger $\frac{dR}{dt}$ at temperatures above -75 C.

The resistance temperature characteristic is very nonlinear. The slope increases with an increasing temperature, Ref. Figure 3.2.2.2-1, which compares nickel, tungsten, and platinum at temperatures from 0 to 300 C. Very little information is available about the characteristics of nickel below about 100 C. There are no commercially available nickel thermometers which are rated for use at temperatures of 20 to 100 K which is the primary concern of this report.

3.2.2.3 Tungsten

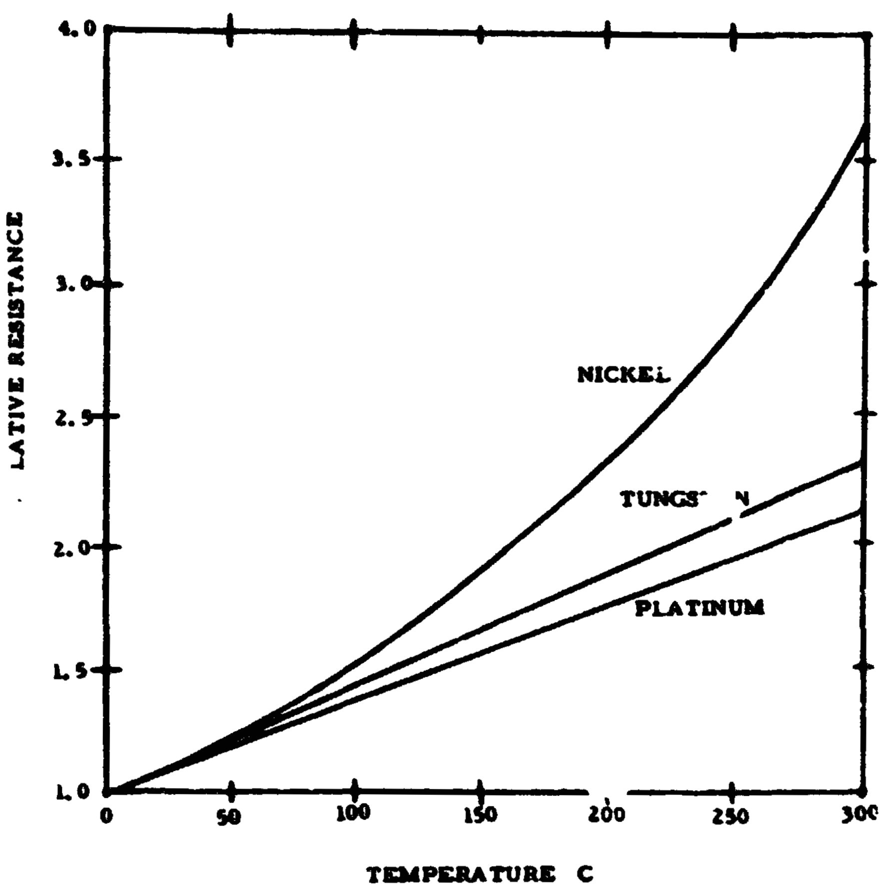
Tungsten has an R-T relationship (Figure 3.2.2.2-1) which is not as well known as that of Platinum. Fully annealing tungsten is impractical, therefore, tungsten sensors have been found to be less stable than well-made platinum sensors. At very low temperatures, the percent change per degree is less than that of platinum. Tungsten has demonstrated good resistance to high nuclear radiation levels. Tungsten's mechanical strength (Table 3.2.2-1) allows extremely fine wires to be handled, resulting in convenience for manufacturing sensors having high resistance values.

3.2.3 Non-Metals

3.2.3.1 Thermistors

Thermally sensitive resistors are semiconductor elements which exhibit resistance changes with a change in temperature. Unlike wire type RTT's, which have positive temperature coefficients and fairly linear curves, thermistors have a large negative temperature coefficient and nearly exponential curves.

Thermistors are semiconductors of ceramic material made by melting together mixtures of metallic oxide such as manganese, nickel, cobalt, copper, iron, and uranium. Their electrical characteristics are controlled by varying the type of oxide and the physical size and configuration of the element. Thermal sensitivities vary greatly but they are generally more sensitive than thermocouples or RTT's. As a result they can be used over narrow temperature ranges with good accuracies. Thermistors can be fabricated into different shapes while still in the non-cured state. Standard forms now available are beads, discs, washers, and rods.



CHARACTERISTICS OF RESISTIVE
THERMOMETER METALS

Figure 3.2.2.2-1

Beads are made by forming small drops of thermistor material on two parallel fine wires. The material is sintered at high temperature until the leads become embedded tightly in the beads and make good electrical contact. For cryogenic use the beads are usually mounted in evacuated or gas-filled glass bulbs. Resistance values of 300 ohms to over 100 megohms at room temperature are available in glass probes of approximately 0.1 inch diameter and 1/4 to 2 inches in length.

Discs and washers are made by pressing thermistor material under several tons pressure. These round pieces are sintered and then silvered on the two flat sides. Discs normally range from 0.1 inch to 1 inch in diameter and 0.020 inch to 0.5 inch thick. Resistance values from 5 to 10 K ohms can be produced. Washers may be mounted on a bolt singly or as a stack with terminals between such that they may be connected in series or parallel.

Rods are extruded through dies to make long cylindrical units which are normally 0.05, 0.11, or 0.17 inch in diameter and from 1/4 to 2 inches long. Leads are attached to the ends of the rods. Resistance values can be made from 1 K to 150 K ohms. The major advantage of rods over other types of thermistors is the possibility of producing high resistance units with moderate power handling capacity.

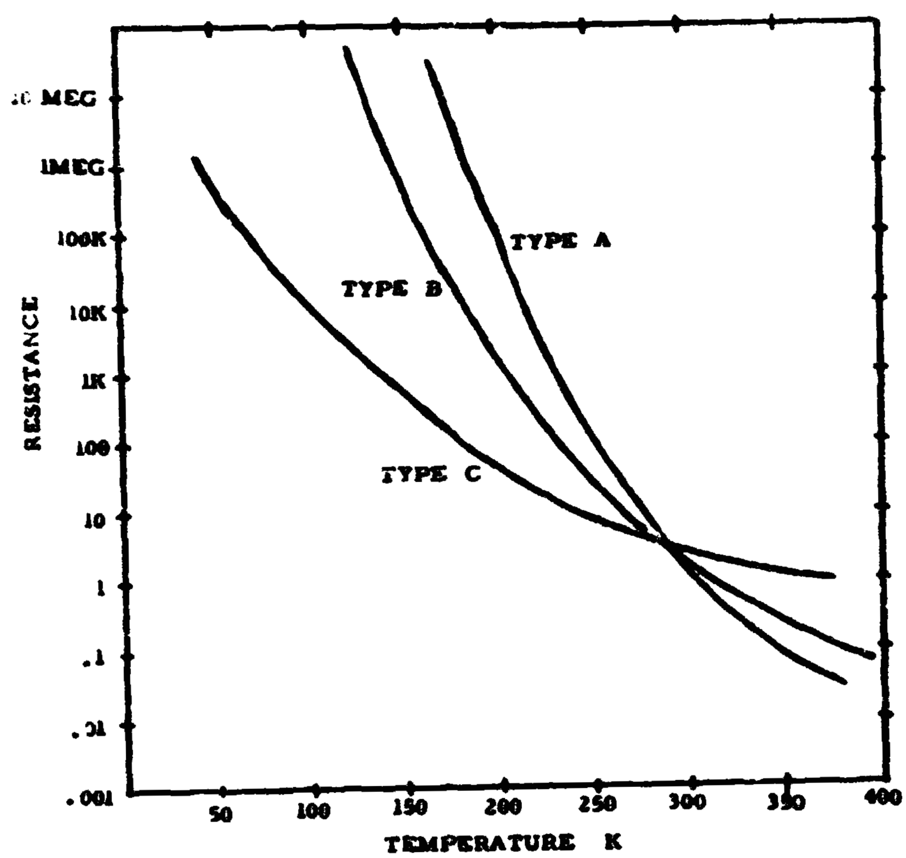
The resistance of a thermistor is solely a function of its absolute temperature. Reference Figure 3.2.3.1-1. The temperature coefficient of resistance for a thermistor (α) is usually expressed as percent/degrees K. Thermistors of different materials run from -3% to -5.8%/K at room temperature as compared to 0.3% for platinum. Thermistors have many advantages over other temperature measuring devices, foremost being their extremely high temperature sensitivity, about ten times that of metal resistance thermistors. Another advantage is that their resistance at the operating temperature is sufficiently high to make lead resistances negligible. The major disadvantage of thermistors is their nonlinearity; however, systems have been developed to compensate for this. The low temperature limit is a result of insensitivity in the measuring system when the thermistor resistance becomes very large. Typical values of resistance and at liquid oxygen temperatures are in the order of 100 K ohms and -11% per degree K. This results in a change of 11 K ohms per degrees K at LOX temperature. This characteristic makes thermistors very difficult to use when large temperature excursions need to be measured. However, they are particularly useful for narrow ranges of measurement.

3.2.3.2 Carbon Resistors

Various kinds of carbon resistors have been used to measure cryogenic temperatures; the Allen-Bradley being the most widely used. Several experimentors [4] [5] have developed an interpolation formula to describe the resistance-temperature relationship shown in Figure 3.2.3.2-1.

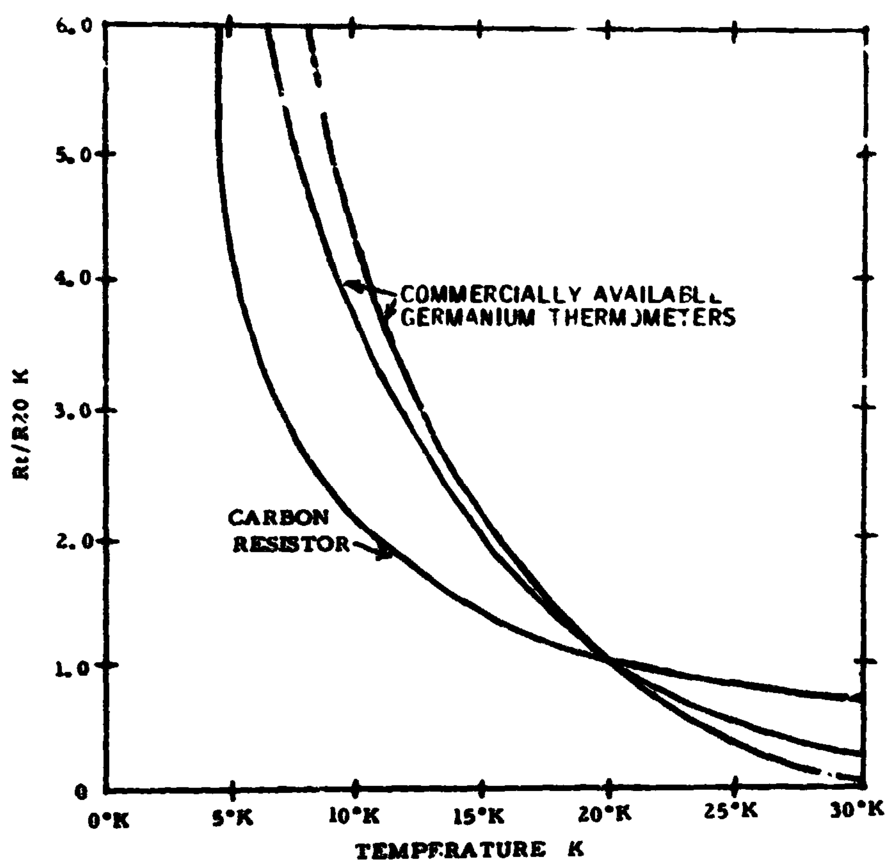
At extremely low temperatures (below 20 K), carbon resistors are very sensitive to temperature. They have been used mainly for research purposes, for temperature measurements from about 0.1 K to 20 K with good results.

Space Division
North American Rockwell



Resistance-Temperature Characteristics Standard Thermistor Disk, Washer, Rod, and Glass Probes for LOX Use

Figure 3.2.3.1-1



RESISTANCE-TEMPERATURE RELATIONSHIPS
OF NON-METAL TEMPERATURE SENSORS

Figure 3.2.3.2-1

The principal disadvantage has been an appreciable nonreproducibility on thermal cycling. In a paper by Straus [5], the stress resistance effects were noted and greatly reduced by heat treating a 1/2 watt resistor, then removing the molded epoxy case and mounting in a probe with strain relief at the end supports.

3.2.3.2 Germainum Semiconductors [2]

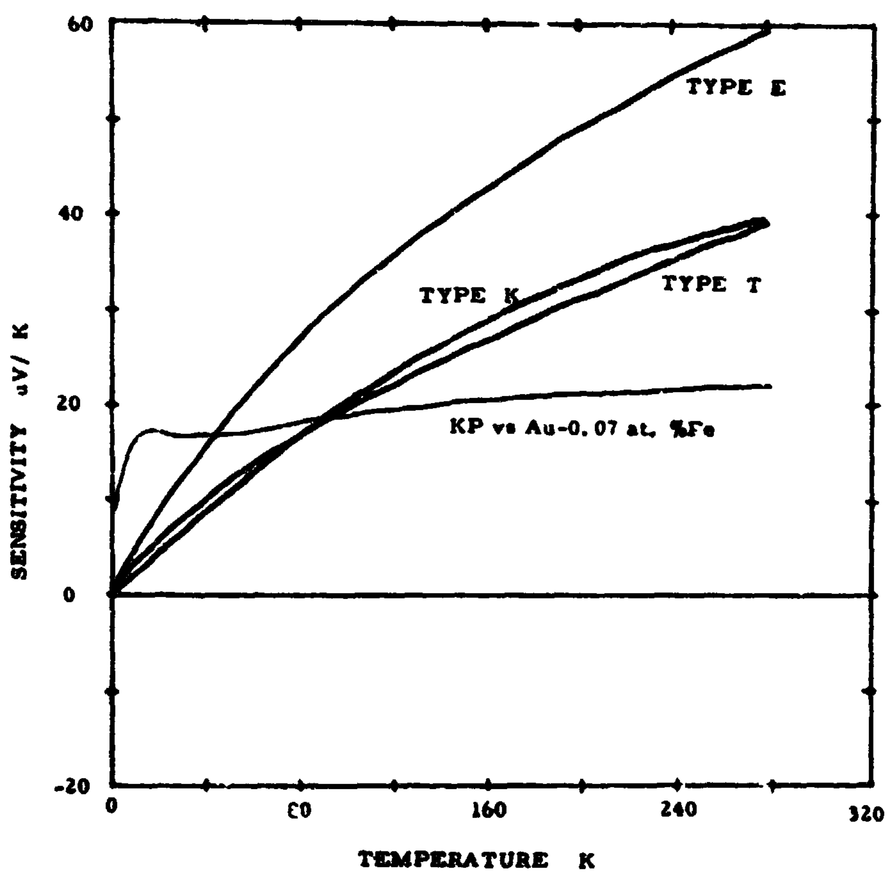
Germainum resistance thermometers are available from several commercial sources. The resistance element is a small single crystal. Because the resistivity is high the element can be short and thick. It is mounted strain-free in a protective capsule. The resistance-temperature relationship for the commercially available Germainum thermometers [2] having somewhat different impurity contents are shown in Figure 3.2.3.2-1. They are quite nonlinear and above 15 K platinum has a greater percentage change per degree. The R-T relationship for these semiconductors is very complex and requires many calibration points.

3.2.4 Thermocouples

Thermocouples are used as temperature transducers because of their inherent accuracy, measurement range, fast response and reliability. Sensor operation is based on the Seebeck effort [7] in which an electric current flows in a loop of two dissimilar metals when the junctions are held at different temperatures. If the thermocouple circuit is open, an electromotive force (emf) will be developed at the terminals, whose magnitude and polarity depend on properties of the metals and on the temperature difference. In practice, one junction is considered a reference and the temperature at the second junction is then found by measuring the emf and referring to calibration tables. If the difference between two temperatures is desired both junctions can be used for measurement and no reference is necessary.

Thermocouples, because the sensing junction can be reduced in size, have the advantage of fast response time and little disturbance of the medium or object being measured. They also have a very low voltage output which must be measured. This disadvantage is accentuated at low temperatures where the thermoelectric power, $\frac{dE}{dT}$ is usually smaller than at higher temperatures (Reference Figure 3.2.4-1).

As stated by Corruccini [6], thermocouples have a less familiar but very serious disadvantage, especially at cryogenic temperatures. The net emf not only depends on the materials used for the two wires but also on material inhomogeneities which, if located in a temperature gradient, will introduce parasitic voltages. These inhomogeneities may exist due to variations in chemical composition or may consist of crystal lattice imperfections introduced, for example, by kinking the wires.



Seebeck coefficients vs. temperature for standardized thermocouple types E, K, T, and for KP vs. Au-0.07 at. % Fe.

Figure 3.2.4-1

Although many materials can be combined to produce a thermoelectric effect, certain pairs have become standard. Those most commonly used in the United States are classified by the Instrument Society of America as in Table 3.2.4-1. Type E (Chromel/Constantan) produces a high and stable emf over the specified ranges. Output increases from 20 μV/deg K at 60 K to 40 μV/deg K at 120 K. Type E is especially useful for differential measurement, since the large output allows easy amplification.

Type J (Iron/Constantan) is widely used because of low cost and high output. The emf increases from about 26 μV/deg K at 80 K to 63 μV/deg K at 1080 K. Type K (Chromel/Alumel) has an output of about 25 μV/deg K from 80 to 240 K.

Type T (Copper/Constantan) is generally useful to 80 K. The emf output increases from 10 μV/deg K at 40 K to 25 μV/deg K at 240 K. Experimental tests and calibration at the National Bureau of Standards, Boulder, Colorado [7], between 4 and 280 K have been conducted using Chromel, copper, "normal" silver, Constantan, Alumel, and gold - 0.07 at. % iron. Many thermocouple combinations can be made from these materials; however, the three pairs widely used in the cryogenic temperature range are Copper vs. Constantan (Type T), Chromel vs. Alumel (Type K) and Chromel vs. Constantan (Type E). A fourth combination which is receiving increasing use is Chromel vs. gold - 0.07 at. % iron. This thermocouple is particularly important because of its relatively high sensitivity at cryogenic temperatures. Figure 3.2.4-1 compares the four types of thermocouples most commonly used at cryogenic temperatures.

Table 3.2.4-1 ISA Accuracy and Range Values for Common Thermocouples

TYPE	THERMOCOUPLE	FULL RANGE, DEG F	ACCURACY, DEG F OR PERCENT, OVER RANGE, DEG F			
			ISA STANDARD LIMITS		ISA SPECIAL LIMITS	
E	CHROMEL/CONSTANTAN	32 - 600 600 - 1600	± 3F ± 1/2%		DATA NOT AVAILABLE	
J	IRON/CONSTANTAN	-310 TO +1,400	±4 DEG F ±3/4%	0 TO +530 +530 TO +1,400	±2 DEG F ±3/8%	0 TO +530 +530 +1,400
K	CHROMEL/ALUMEL	-300 TO +2,500	±4 DEG F ±3/4%	0 TO +530 +530 TO +2,500	DATA NOT AVAILABLE	
T	COPPER/CONSTANTAN	-310 TO +750	±2% ±1-1/2 DEG F ±3/4%	-150 TO -75 -75 TO +200 +200 TO +700	±1% ±3/4 DEG F ±3/8%	-300 TO -75 -75 TO +200 +200 TO +700

In space applications, indicators and reference junctions are usually remote from the measurement points. Connections to the thermocouples must therefore be made with extension wires [9] specially selected not to introduce errors in the measuring circuit. Lead wires are often composed of the same materials as the thermocouples. However, for thermocouples of the more expensive materials (gold, platinum) the cost makes it more practical to choose wires of copper and copper-nickel alloy that closely match the required characteristics. Extension wire may be obtained as insulated matched pairs, with color-coded conductors and insulation. Twisted pairs are also supplied, to provide high rejection of electromagnetic interference.

Various insulations are available, selected for flexibility and diameter as well as resistive to temperature extremes, moisture, corrosion or abrasion.

The most satisfactory and easily reproducible reference junction is the Ice bath consisting of a mixture of shaved ice and water. However, ice type junctions are impractical for aerospace use. There are several electrical, solid state reference junctions available. The basic design employs a temperature-sensitive material thermally bonded to the cold-junction thermocouples. The resistance-temperature curve matches the emf curve of the thermocouple material. The voltage change is then equal and opposite to the cold junction thermal junction over a wide temperature range. The self powered type of compensation provides a constant voltage, allowing the electrical reference junction compensator to be placed in remote parts of the system.

Even though thermocouples and extension wires are properly selected, errors can be introduced during installation and service. Several precautions should therefore be observed. For example, excessive deformation of thermocouple wire can adversely affect accuracy, so bending, flexing, or stretching should be avoided.

The thermocouple sensing element should be placed so that the measured temperature is representative of the equipment or medium to be monitored. If the thermocouple is immersed in a fluid, the depth of immersion should be sufficient to reduce heat transfer away from the measuring junction. A minimum depth of ten times the outside diameter of the protection tube or thermowell is recommended by the NBS [7] as "usually adequate to prevent errors due to thermal conduction."

3.3 TRANSDUCER DESIGN CONSIDERATIONS

Several types of sensor elements have been discussed. In order to cover some of the important design considerations of transducers used to measure cryogenic temperatures, the wire wound sensing element using platinum wire has been chosen as a typical example to discuss difficult design problems. In general, wire wound resistance thermometers have several advantages over the other types of measuring devices. Not only are they suitable for measuring large temperature differences and high temperatures, but their high accuracy makes them especially valuable in narrow range and cryogenic applications.

Well designed resistance thermometers have excellent stability. Some error sources which must be considered and minimized to achieve the accuracy requirement of future space applications are:

Self heating	Response lag
Stem conduction	Transducer configuration

In order to minimize self heating discussed in the temperature-bridge section, transducer resistances as large as the size or configuration of the instrument will permit are required when cryogenic temperatures are being measured. Platinum wire resistance diminishes rapidly in the cryogenic temperature region. Therefore to minimize errors and to increase resolution, transducers are selected for large ice point resistance values. As an example, the resistance of pure, annealed, strain-free platinum wire varies in accordance with the relationships below:

At 32 F $\quad \frac{RT}{Ro} = 1$

where RT = element resistance at temp T F
Ro = element resistance at 32 F

At -320 F $\quad \frac{RT}{Ro} = 0.1893198$

and At -426 F $\quad \frac{RT}{Ro} = 0.0036070$

The relationships above indicate that a transducer with a resistance (Ro) of 100 ohms at 32 F would have the resistance diminish to 18.9 ohms at -320 F and to 0.36 ohms at -426 F. In order to improve sensitivity and to minimize such effects as leadwire resistance variations, element resistances must be selected high.

3.3.1 Sensor Configuration

Sensor configuration design involves a tradeoff of transducer size, weight, operating temperature range, signal conditioning design, platinum wire diameter, and wire winding area. The limitations of the resistance value which can be wound for a given probe type transducer is a function of the length and diameter of the probe and the element wire size. For example, a probe with an ice point resistance of 2500 ohms requires a relatively large winding area Using 0.0007 diameter platinum wire, the length of element winding is determined below.

$$\text{Wire length (inches)} = \frac{\text{Total Probe Resistance}}{\text{Element Resistance/ft}} \times \frac{12 \text{ inches}}{\text{ft}}$$

$$= \frac{2500 \text{ ohms}}{120 \text{ ohms/ft}} \times 12$$

$$= 250 \text{ inches}$$

If we assume a constant diameter probe of outside diameter equal to 0.340 inch and mandrel diameter of 0.287 inch (at the ℄ of wire), the probe sensing element length can be determined as calculated below.

Circumference of probe	$= \pi \times$ diameter at ℄ of wire
	$= 3.14 \times 0.287$
	= 0.901 inches/turn
No. of wire turns	$= \frac{\text{Wire Length}}{\text{Length/Turn}}$
	$= \frac{250 \text{ inches}}{.901 \text{ inches/turn}}$
	= 277 turns at a pitch of 0.005
Element sensing length	$= 277$ turns $\times .005$
	= 1.38 inches

This length may or may not be acceptable for a given application. For example, in the case of a feedline measurement, the ideal sensing configuration may be to concentrate the sensing element as close to the center as possible to minimize stem conduction effects and to penetrate the feedline to a desired depth. A probe of the shortest element length comes closest to achieving this ideal configuration. Performing the calculations with an element wire diameter of 0.0005 inch results in an element length of 0.680 inch which reduces the element length of the 0.001 inch wire by approximately one half.

The 0.680 element length is a definite improvement over the original 1.38 inch length. At this point a number of tradeoff factors must be considered. The smaller size wire may be more susceptible to failure under vibration and also may require more care during the manufacturing process (which may result in higher cost). Another factor may be to increase the probe diameter to shorten the sensing element length. The tradeoff resulting from this change is to increase instrument mass thus affecting measurement response and also increasing susceptibility to stem conduction. The larger diameter may increase unit mass to the extent that material may have to be added to the threaded end in order to survive the dynamic environment.

3.3.2 Physical Configuration Influence on Temperature Measurements

The fundamental principle of platinum resistance thermometry is that the transducer registers a temperature measurement equal to its body temperature in the region of the sense wires. Any influence which tends to alter this body temperature with respect to the measured temperature will result in a "measurement error." This fact is an inescapable consideration in the selection of a temperature transducer for a given measurement. Stem conduction error is the most common example of this influence and is a serious error source in cryogenic measurement applications. Other configuration influences may not be so obvious.

In a Saturn S-II application two configurations of temperature transducers were installed at approximately the same location of the center engine LOX feedline accumulator. This measurement redundancy resulted from a flight system measurement and a hardwire measurement with each system using a different transducer configuration.

The center engine LOX feedline accumulator is charged with helium gas during engine run. The accumulator temperature measurements provide an indication of helium gas or LOX in the accumulator. During a static firing test of the Saturn S-II, the flight (telemetry) and the ground (hardware) measurements indicated that two opposing conditions were occurring. The flight probe indicated that temperature within the accumulator was rising while the ground probe indicated that temperature was dropping. These indications occurred after the liquid surrounding the probe was replaced with helium gas.

The data in Figure 3.3.2-1 indicate an initial warming during accumulator helium charging. Following this initial warming, the measurements both indicate a cooling. The flight measurement then reverses and shows a continuous warming but the ground measurement continues cooling and drops to a subcooled indication and remains in the subcooled state for over 60 seconds before indicating a warming trend. Figures 3.3.2-2 and 3.3.2-3 show details of the internal configuration of the probes. Both probes were found to have an internal volume which could entrap LOX. The flight probe volume is ported at both the tip and the base; the ground probe volume is ported only at the tip. Both probes then entrap LOX and the significance of this is that LOX with a helium blanket will boil into the partial pressure condition of helium and cause subcooling of the probes.

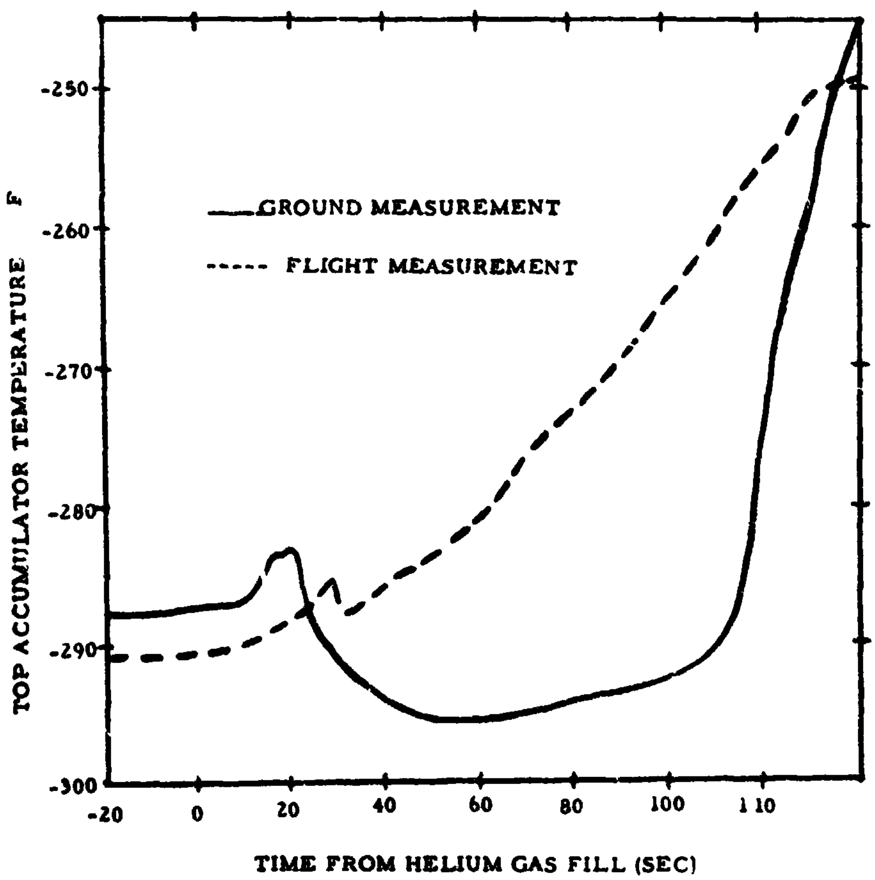
Based on the data derived from laboratory tests, the following deductions were determined:

a. The initial warming indication is caused by the probes sensing the stratified or warm LOX from the bleed line and accumulator top as the liquid level decreases and empties from the bottom.

b. When the probe was uncovered, its external wetted surface and internally trapped liquid boils or evaporates into the partial pressure condition of the helium pressurant. The heat for vaporization is extracted from the probe and its residual liquid causing the cooling indication. The variation between the flight and ground probe is a function of the volume of internally trapped liquid and its escape path. The flight probe has an easier escape path (open on both ends) yielding a much shorter cooling period.

c. When the probe's internal liquid is either spurted out or boiled off, heat extracted by the probe from the warmer helium gas generates the final rise in temperature indication.

The probe configuration ideally preferred for liquid/gas measurements is shown in Figure 3.3.2-4. This configuration eliminates void spaces of the transducer which could entrap liquid. In addition, the relatively sharp edge of the probe reduces adhesion of liquid to the probe assuring the quick drainage of liquid.



FLIGHT AND GROUND MEASUREMENT
TOP ACCUMULATOR TEMPERATURE

Figure 3.3.2-1

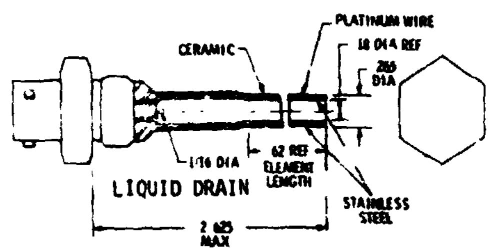


Figure 3.3.2-2 Flight Temperature Transducer

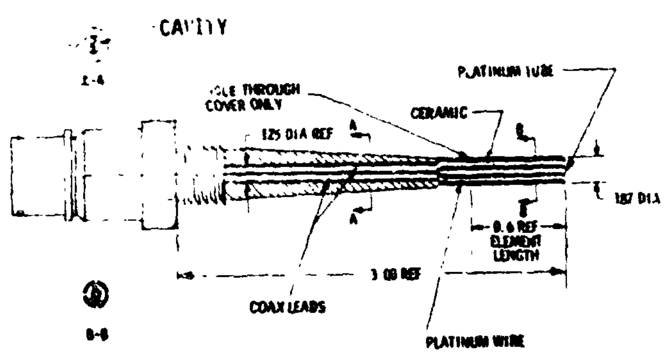


Figure 3.3.2-3 Ground Measurement Temperature Transducer

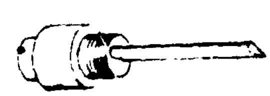


Figure 3.3.2-4 Liquid/Gas Temperature Probe

For the measurements described, the flight configuration more closely resembled the actual temperature conditions since laboratory tests and the data verified that less liquid was entrapped in this configuration.

3.4 BRIDGE DESIGN CONSIDERATIONS

The electrical aspect of measuring temperature with a platinum thermometer consists of a precise measurement of resistance ratio. Therefore, to determine the temperature sensed by a platinum thermometer, measurement of its resistance can be attained by comparison methods based upon a resistance bridge. Because of the extreme reproducibility of the resistance change with temperature, a very high degree of precision, of the order of 1.0 PPM can be attained. In making measurements to this precision, several major design considerations should be evaluated when selecting a particular bridge:

a. Effects of the resistance of leads connecting the thermometer element to the resistance measuring bridge circuitry.

b. Thermoelectric emf's developed by temperature changes in the thermometer, its leads, connector contact resistances, and other parts of the bridge circuitry.

c. The limited amount of electrical power which may be dissipated in the thermometer and in the bridge resistors without causing a significant uncertainty due to self-heating.

d. Reactance of thermometer, leads, and bridge circuitry should be considered where fast response is desired.

e. Linearity problem can be introduced when thermometer is combined with a bridge to form a temperature measuring system, e.g., most linear transducers will produce a highly nonlinear temperature-system output if not used with proper bridge.

f. Noise - electrical interference can be critical if low level output bridge is considered, e.g., noise level of 50 millivolts in a low level 0-100 millivolts system can be catastrophic. Proper shielding and grounding must be observed to obtain noise attenuation less than 5 millivolts.

g. Interaction between each measurement in a multiple bridge system using one excitation power supply should be minimized by elimination of a common impedance.

h. Loss of bridge output sensitivity can occur if output multiplexing system input impedance is not considered.

Because the platinum thermometer provides a widely accepted standard for measurement of temperature over a relatively wide range, numerous techniques for measuring its resistance have been developed. However, the basic technique is to determine the temperature sensed by a resistance thermometer by measurement of its resistance by comparison methods based upon a resistance bridge.

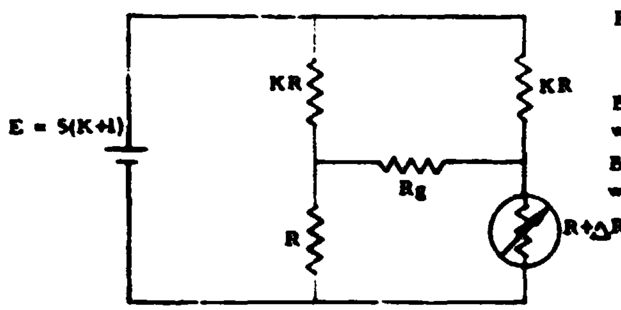
Where bridges are used as a comparison device and once the bridge is in balance, the value of the thermometer resistance can be calculated by a simple ratio equation, or a bridge output voltage proportional to the deviation from the balanced condition representing the thermometer resistance change can be determined. To calculate this deviation, the bridge sensitivities for the change in resistance and the temperature causing it, must be known. Therefore, when a bridge is selected to be used as a comparison device, bridge equations for balanced condition and both sensitivities should be derived. Numerous technical papers have been written describing the derivations of these equations for various types of basic bridges and therefore will not be discussed in this report. However, the advantages and disadvantages relating to a particular measurement problem when making a selection from a list of various types of bridges available will be discussed.

In reviewing different types of bridges, it became apparent that these bridges are variations of a basic bridge method which can be described as either a half or a full bridge (see Figures 3.4-1 and 3.4-2). From these basic methods, variations can be added such that a full or half bridge can become either symmetric where $K = 1$ or asymmetric where $K \neq 1$ based on its particular usage. Therefore, basic bridge methods can be developed with variations added to a more complex method or low level output bridge such as Mueller, Smith and Callendar bridge methods. For example, (1) a half bridge method is selected for use when there are a large number of measurements required which would reduce the cost per measurement, (2) the half bridge is then varied to an asymmetric bridge for improvement in linearity and sensitivity over a symmetric bridge, (3) the bridge is then either balanced or unbalanced depending upon its temperature range and span, (4) the bridge is considered for either high level or low level output based on self-heating requirement, and (5) finally, leadwire compensating circuit is added to the bridge. Thus, the finalized bridge would look similar to a Siemens three-wire bridge.

The basic full and half bridge variations can be summarized as follows:

<u>The full bridge variations</u> (see Figure 3.4-1)

- Can be used as a high level bridge output (0-5 v) or as low level bridge output (0-100 mv)
- Can be used as a symmetrical bridge where $K = 1$, as asymmetrical bridge where $K \neq 1$.
- It is a wheatstone bridge using only one excitation power supply.
- Can be used as a balanced or unbalanced bridge output.
- Leadwire compensation circuitry is required if thermometer is located at a distance.



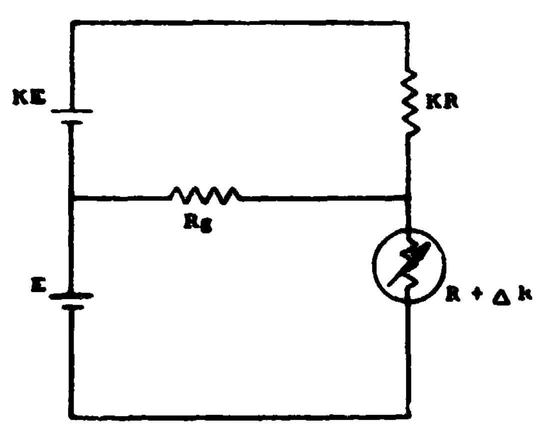
Rg is load or
telemetry input
if used.

Bridge is symmetric
when K = 1

Bridge is asymmetric
when K ≠ 1

Full Bridge--Wheatstone

Figure 3.4-1



Rg is load or
telemetry input
if used.

Bridge is symmetric
when K = 1

Bridge is asymmetric
when K ≠ 1

Bridge uses two
power sources.

Half Bridge

Figure 3.4-2

The half bridge variations - (see Figure 3.4-2)

Can be used as a high level bridge output (0-5 v) or as low level bridge output (0-100 mv).

Can be used as a symmetrical bridge where K = 1, or asymmetrical bridge where K ≠ 1.

Two power supplies replace the single supply and the two reference arms of a full bridge.

Can be used as a balanced or unbalanced bridge output.

Leadwire compensation circuitry is required if thermometer is located at a distance.

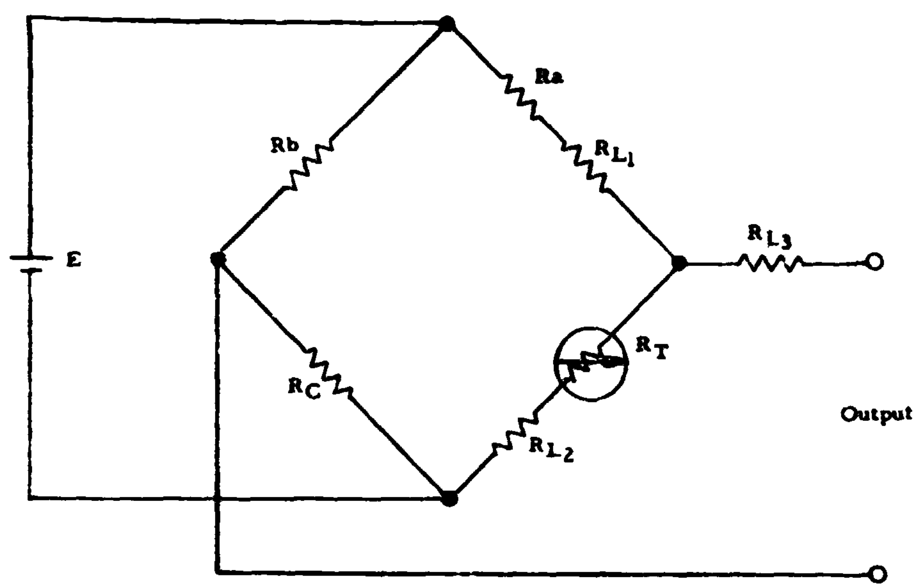
It is important that the two basic bridge designs are usually varied in accordance with consideration to one or more of the above listed major design considerations. Therefore, when selecting a specific type of bridge, major design considerations should be a factor for a particular measurement problem. Lack of understanding of major design considerations could make designing of a suitable bridge a frustrating task. A thorough understanding of design considerations would prevent an inferior bridge design. It is difficult to assign importance to any one of the above listed design considerations. It is felt that all of the design considerations should be seriously evaluated prior to finalization of a particular type of bridge. Therefore, an in depth discussion of each major design consideration related to a particular need would be worthwhile; and therefore, these discussions are included.

3.4.1 Bridge Lead Resistance

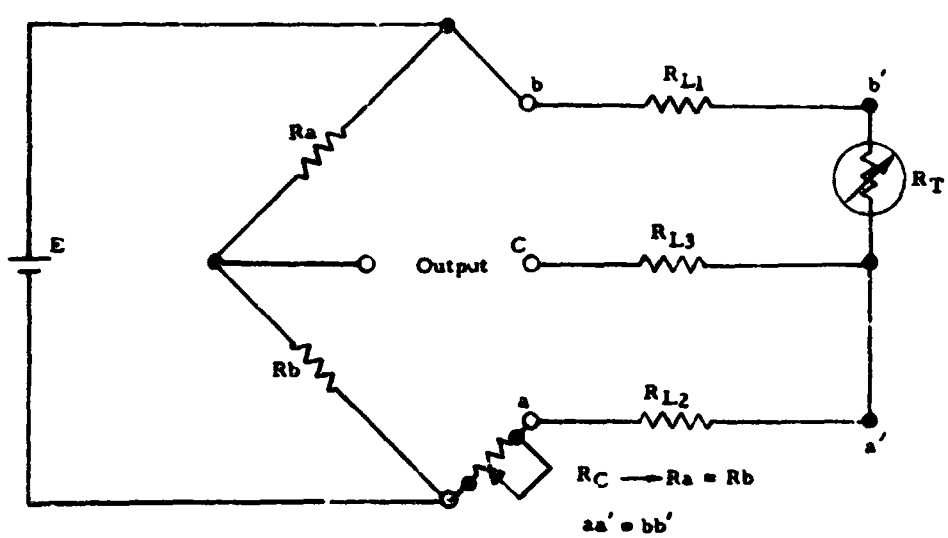
Numerous bridges, to name a few such as Callendar-Griffiths, Mueller, and Seimen, have been developed to minimize the effects of leadwire resistance connecting the thermometer element to the resistance measuring bridge circuitry. For temperature measurement systems used in a large vehicle system, where bridge circuitry and thermometer element are usually a considerable distance apart, lead resistance as much as 2.5 ohms to 5.0 ohms variations can be experienced. Figure 3.4.1-1 depicts a full bridge with a typical lead resistance problem. Table 3.4.1-1 shows typical percentage of error experienced for different temperature ranges measured due to the lead resistances.

Calculation for determining lead resistance can be made using the following equations for bridge depicted by Figure 3.4.1-1.

$$A = \frac{100\, r_L}{r_T + r_L + 0.5} \quad \text{where all lead resistances are equal}$$



Three Wire Bridge



Three Wire Compensated Bridge

Figure 3.4.1-1

where

A = error due to leads as a percentage of full scale output voltage.

$r_L = R_L/\Delta R_T$ where $R_L = R_{L1} = R_{L3} = R_{L2}$

$r_T = R_{T1}/\Delta R_T$

R_{T1} = minimum resistance of sensor

ΔR_T = full scale change in resistance of sensor

When lead resistances are not equal, error in bridge is:

$$B = 100\ (R_{L1} - R_{L2})/\Delta R_T$$

where

B = error as percentages of full scale, and R_{L1} and R_{L2} are unequal.

In the above two equations lead resistance R_{L3} is unimportant since it is in series with the load. Table 3.4.1-1 shows errors calculated by equations (1) and (2) when lead resistances varied between zero and 2.5 ohms (R_{L1} = R_{L2} = 1.25 ohms). Percent errors are largest calculated for all combinations of lead resistance between zero and 2.5 ohms at either balanced or full scale. Except for very small R_{T1}, errors are approximately proportional to the magnitude of lead inequalities, and nearly independent of the minimum lead resistance so that the results are representative of the case where leads vary from 2.5 ohms to 5.0 ohms. It is also noted that the effects of lead resistances are also suppressed when $R_b = R_c$ and the bridge is balanced. Table 3.4.1-1 shows that when leads R_{L1} and R_{L2} are equal, percent of error is much less than when R_{L1} and R_{L2} are unequal. However, $R_{L1} = R_{L2}$ is unrealistic since it is difficult to attain controlled lead resistance during procurement. Figure 3.4.1-1 shows what can be done to compensate for lead resistance error by means of a three wire bridge, provided the lead resistances are equal. A close study of Figure 3.4.1-1 will show that since $R_a = R_b$, the bridge is in balance only when sensor arm has the same resistance as the adjacent arm; therefore, the same amount of lead resistance is introduced in the sensor as in the adjacent arm, and the amount of the lead resistance does not affect the balance point, provided the lead resistances are equal. Figure 3.4.1-1 also depicts the complexity of lead resistance problem because lead resistance inequality can be substantial since wire varies a significant amount in diameter and even more in cross-sectional area. In addition, individual connections, connector contacts, and relay contacts if relays are used for calibrations, can contribute considerable additional individual lead variation. Lead resistance problem can be classed as (1) variation for the case when all leads vary simultaneously, and (2) deviations of resistance from one lead wire to another. As stated above, many variations in bridge

Table 3.4.1-1. 3-Wire Bridge Error

Range F	Min. Resistance	Max. Resistance	A% of Full Scale	B% of Full Scale
-435 to -400	0.8	12	±16.2	±21.9
-335 to -285	77.2	137.2	1.15	4.2
-305 to -255	113.1	173.1	0.86	4.2
-100 to 0	352.1	464.6	0.24	2.3
-425 to +75	2.1	547.3	0.045	0.46
0 to 100	464.6	574.6	0.24	2.3
+100 to +200	574.6	682.8	0.20	2.3
+200 to +300	682.8	789.2	0.17	2.3
+300 to +400	789.2	893.7	0.15	2.4
+400 to +500	893.7	996.5	0.13	2.4

NOTES: A = Lead errors when leads are of equal resistance for excitation as a percent of full scale output

B = Lead errors as a percent of full scale and R_{L1} and R_{L2} are of two different lead resistances; $R_{L1} \neq R_{L2}$

Computation based on a platinum thermometer with 500 ohms at 0 C (ice point).

design have evolved in correcting lead resistance problems such as Seimens' three-wire bridge, Smith's bridge, and Rosemont's triple bridge. These bridges will be discussed later for their applicability to solution of a particular lead resistance problem.

3.4.2 Thermoelectric emf

Thermoelectric emf developed by temperature changes in the thermometer, its leads, connector contact resistances, and other parts of bridge circuitry could be a problem. The major consideration for this problem is to avoid dissimilar metal usage in connector contacts and connecting wires in the overall system, particularly in areas where temperature variations are imminent. Since the thermometer region appears to be where the greatest temperature variations occur, careful evaluation of thermometer construction should be made. Also, controlled environment for the bridge and its excitation power supply would minimize the thermoelectric emf problem.

3.4.3 Self Heating

Self heating of resistance thermometer may vary from one application to another, and can be considerable when thermometer is used for cryogenic measurements due to its low resistance at cryogenic temperature. Therefore, the limited amount of electrical power which may be dissipated in the thermometer and in the bridge resistors could cause a significant uncertainty in the measurement. It has been considered throughout the industry that 20 ma (RMS) of current through the thermometer or 10 milliwatts is acceptable without causing any uncertainty in the measurement. Reason for this is that the thermal time constant is long compared to excitation period; therefore, effective heating current in thermometer element is related to RMS current and not the peak current.

Example: A 450 ohm platinum in liquid oxygen (54.7 K) has an offset of 0.1 K for excitation current of 25 ma RMS.

Method for use of current greater than 25 ma RMS can be attained by use of time-sharing techniques such as multiplexing excitation power source to the sensor and/or bridge resistors.

Example: 450 ohm platinum shows a negligible self heating when excitation with peak currents of 100 ma with duty cycle of 1/60 RMS current is 1.6 ma.

When determining whether a full bridge or a half bridge should be used, a practical condition is the self heating limitation within the thermometer element, expressed as the number of watts dissipated within the probe to yield one degree temperature rise for a particular set of ambient conditions. The self heating limitation is generally provided by the thermometer manufacturer as power sensitivity (W_m), or power which can be dissipated in the thermometer to achieve a given rise in temperature. This, in turn provides a constraint upon the excitation source for either full or half bridge systems. Equations for the constraint are generally given by the manufacturer; for example, for the following basic type of bridges:

Half bridge

$$E \le \sqrt{R_p' W_m}$$

where

R_p' = minimum expected value of R_p (probe resistance)

W_m = power sensitivity

E_x = power source adjacent to the probe

Full bridge

$$E_{MAX} = \sqrt{W_m R_p}$$ = value which limits the self heating error to 0.5 K.

Where power limitation is critical, full or half bridges can be designed for low level output. Where larger bridge output voltage is desirable, the bridge can be pulsed. In this manner, the bridge output should be a pulsed square-wave. However, the duty cycle must be small. If multiple bridges are used and the bridge outputs are multiplexed, the sampling time could be made to coincide with the power pulsing time period.

3.4.4 Linearity

Linearity relative to temperature measurement is much more complicated than it would appear on the surface. Often the designer would look at the linearity curves for various resistive wires and makes a selection on that basis. The crucial element in linearity attainment occurs when the thermometer is combined with a bridge to form a temperature measuring system. The most linear thermometer will produce a highly nonlinear temperature system output if not used with a proper bridge. Conversely, a nonlinear thermometer is often used to obtain linear temperature measuring system. Parameters which could affect system linearity are as follows:

a. Thermometer linearity

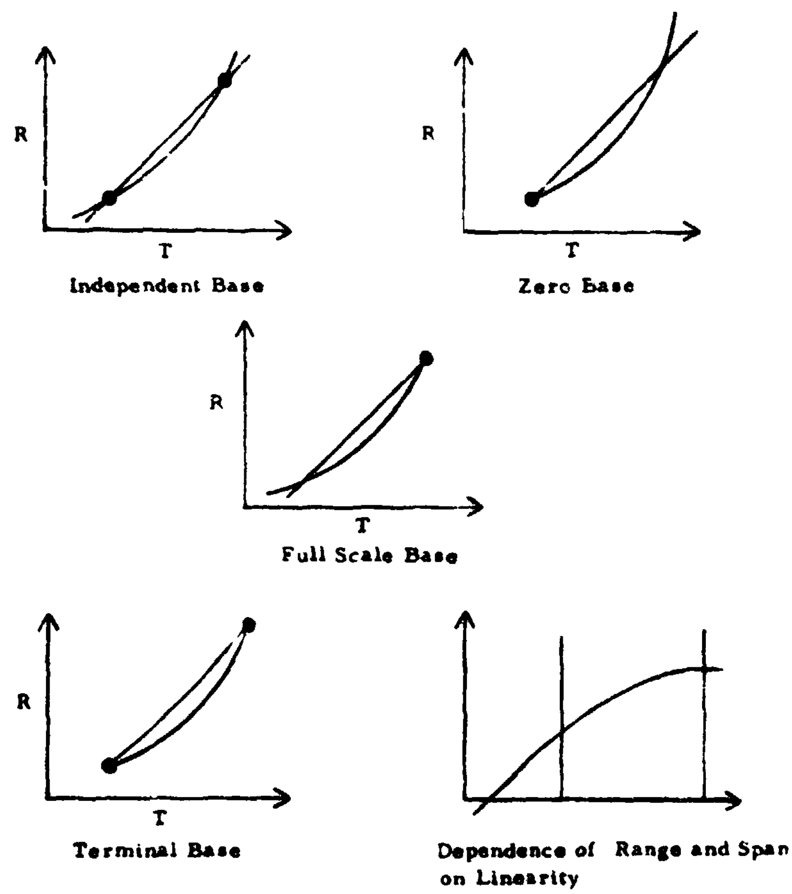
b. Type of bridge used such as symmetrical or asymmetrical bridges

c. Bridge loading

d. Thermometer location

e. High level or low level bridge output

Linearity is commonly stated as (1) independent, (2) zero based, (3) full scale based, and (4) terminal (Figure 3.4.4-1 depicts all four). Independent, which is most commonly used, is obtained by drawing a best straight line through the curve, such that the equal positive and negative deviations of the curve from the line exist. Zero based is obtained by drawing best



Types of Linearity Curves

Figure 3.4.4-1

straight line from the point of origin. Full scale based is exactly opposite to zero based. Terminal is obtained by drawing a straight line between the two end points. Of these, independent linearity is most frequently used with the linearity stated as a fraction of the temperature span in degrees or percentage. It should be noted that any linearity specified usually applies only for a specified span and temperature range. A thermometer which exhibits some degree of linearity over a span of 100 K may exhibit different debrees of nonlinearity depending as to where this span is selected on the resistance-temperature curve. In addition, the narrower the span, the better the linearity. Therefore, a graph of linearity for a specified temperature span does not depict the linearity obtainable for other spans and ranges. With variation of span and range, an inferior thermometer may become superior under selected operating conditions. A full or half symmetric bridge is recommended for usage in obtaining the best linearity. The reason for this is that current flow through the sensor arm is at high asymmetric ratios effectively independent of its resistance. This is not the case for a full or half symmetric bridge. Generally, if a bridge in usage is nulled or balanced, linearity is not a significant problem. However, in cryogenic region balancing the bridge would be difficult due to the low resistance of the sensor element which would limit power applied across it.

3.4.5 Bridge Sensitivity

Bridge sensitivity is generally categorized into two types: first sensitivity relates the bridge output voltage to resistance change about the null and has the dimension of current; second sensitivity relates the output voltage to changes in temperature. In practical bridge designs, maximum sensitivity can be obtained if sensor can be energized with its maximum allowable voltage. It should be noted that the maximum allowable voltage is determined by self-heating power limitation of the thermometer element. Therefore, when designing for maximum sensitivity, self heating limitation within the thermometer should be considered. Also, sensitivity factors could be decreased by the ratio of leadwire resistance to leg resistance; and therefore, sensitivity also becomes a function of the change in leadwire resistance due to ambient temperature variations. Generally, when a particular bridge is selected, its two sensitivity equations should be derived and all parameters included in these equations should be evaluated for environmental variations. In addition, leadwire resistances which are usually not included in these equations, should be considered.

3.4.6 Bridge - Thermometer Temperature System

Accuracy of a selected bridge-thermometer temperature system should be defined as the ratio of the error to the full scale output. Accuracy is usually expressed as "within $\pm$ xxx percent of full scale output." When calculating accuracy, percent error for each subsystem at ambient condition should be considered for the total temperature measuring system, which should include telemetry and data processing if measurement is processed in this manner. Accuracy for a total temperature measurement system can be broken down into sub-blocks as follows.

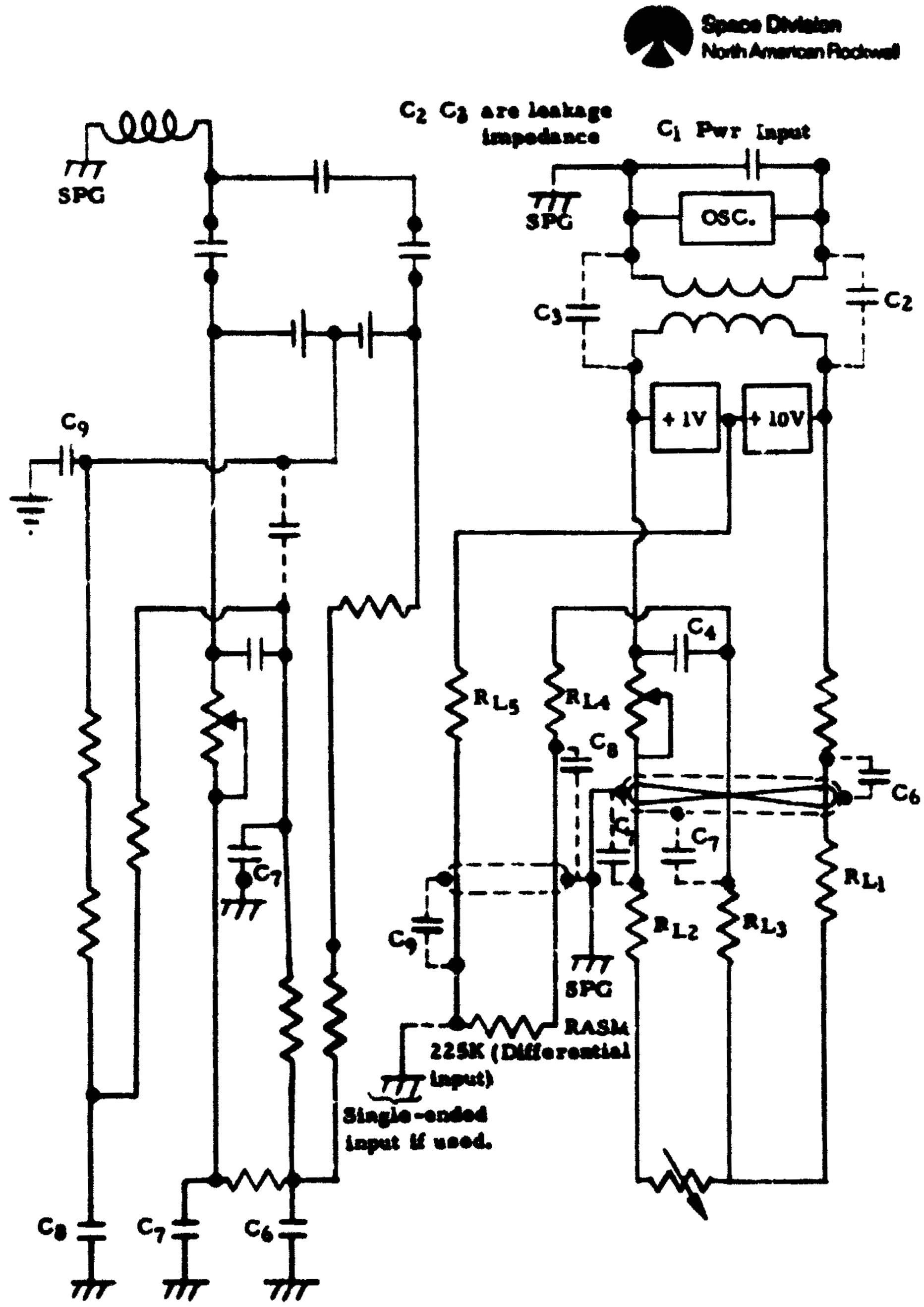
a. Thermometer - Accuracy for a particular span and range can be calculated from the calibration or repeatability data provided by the supplier. However, by rule-of-the-thumb estimate, an accuracy of one percent or less should be sufficient.

b. Bridge and associated components - Accuracy calculation can be complex because power supply, bridge components, and leadwire resistances have to be considered. However, by rule-of-the-thumb estimate, an accuracy of one percent or less should be sufficient if attainable.

It should be noted that when considering accuracy many variations to the total system could introduce errors such as excitation power supply, lead-wire resistances, bridge repeatability, and electrical noise. Therefore, caution should be exercised when specifying total system accuracy.

3.4.7 Noise Reduction

Noise reduction techniques should receive a serious consideration when a half or full bridge is designed for high accuracy low level output (o to 500 mv or less). Noise voltages as much as 50 mv peak-to-peak are realistic with the best of proper shielding and grounding. Sources of electrical interference are many, and include all power generation circuits, utilization, control, transmission, distribution equipment, conductors, and other instrumentation systems in the vicinity of a low level temperature measuring system. Low level system signals are particularly vulnerable to interference, especially when they traverse considerable distances. Higher information accuracy requires even greater interference suppression. A 0.1 percent accuracy would require suppression of three to six orders of magnitude. Suppression by these ratios is usually difficult even with the application of proper shielding and grounding practices. Wherever possible, interference problems should be anticipated during the design of system. Generally, solutions to suppression of noise interference lie in the careful and intelligent application of basic principles of control to the proper design of wiring systems with respect to shielding and grounding, proper choice of thermometers, and the design of bridge circuitry including excitation power supply. Figure 3.4.7-1 depicts a special case in a design of temperature measurement system using an asymmetrical half bridge with a low level output of 0 to 100 millivolts. A discussion of this design relative to noise interference problem may be of value to a system designer. Figure 3.4.7-1 depicts numerous challenging areas where noise injection could possibly enter and degrade the measurement system. Solution to reduction of noise in this system can be complex if all factors attributing to the problem are considered. An example of this complexity is that using twisted shielded wire would minimize magnetic coupling of noise but would increase capacitance between wires and the shield and therefore would make system vulnerable to electrostatic coupling of noise. It should be noted here that the noise coupling is usually due to (1) magnetic coupling, or (2) electrostatic coupling. Generally, the best solution is to eliminate the source of noise and avoid close proximity of electrical and instrumentation wiring.



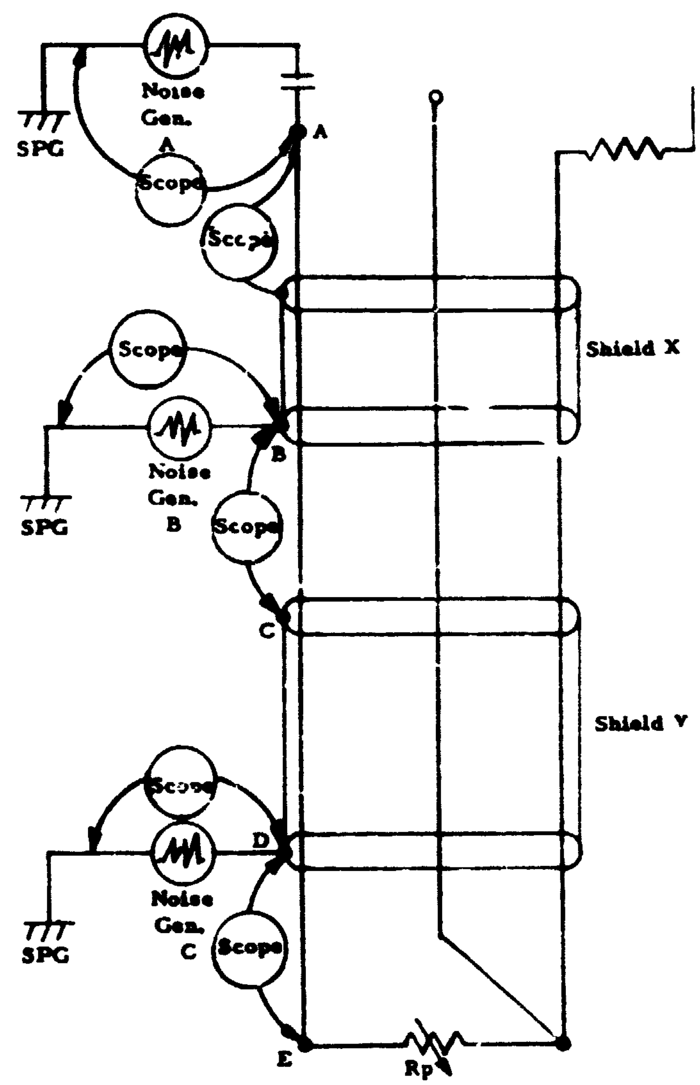
Typical Low-Level Half-Bridge Temp. System Design

Figure 3.4.7-1

However, these solutions may not be practical especially in a space vehicle where wiring space could be critical and a pulsed electrical power is a prime functional requirement. Since temperature measurement system has less priority than vehicle electrical functions, noise solution often is confined to the measurement system. The best way is to reroute the noise interference signals away from the system. Figure 3.4.7-2 depicts how this can be done. First step is to connect noise generators as shown in Figure 3.4.7-2. Second step is to measure noise voltages between points as depicted in Figure 3.4.7-2 using an oscilloscope. As a final step, wherever noise voltages are measured, steps should be taken to reduce the noise voltages to an acceptable level in a low level system (0-100 mv) or a high level system (0-5 v). One method would be to ground the shield directly to the nearest structure rather than to a single point ground (SPG). This should reduce the noise potential between points B and C. An alternate method would be to connect points B and C together. Noise potential between points A and SPG can be reduced by connecting a sufficiently large capacitor between points A and SPG. Since other methods are available, the aforementioned methods should be performed experimentally and may not produce the best results. However, it is suggested that all possible failure modes be induced such as thermometer element (R_p), is open-circuited or grounded on either side to case ground (structure) when experimenting. Another method worth mentioning is to connect a sufficiently large capacitor between the high side of the bridge output and the return side of the +1 v voltage source in the case of a half bridge design, and directly across the output for a full bridge design. When in a high or low level half bridge system where excitation power with two voltage sources is used for multiple half bridges, the capacitor should not be connected from the high side of the bridge output to the common return for noise reduction. Reason for this is that if one thermometer element is grounded or open circuited, interaction between the bridge containing the open circuited thermometer element and other normal bridges can occur, thus degrading the measurement outputs of these bridges.

3.4.8 Interaction

Interaction between measurements in a multiple temperature system can be a problem if a half bridge system is used. Usually the cause of interaction is due to a system which has a common impedance point such as split power sources as in a half bridge and a thermometer failure. Solution here would be to minimize the common impedance point which is not difficult to attain since most often it occurs in the power supply where impedance can be made very low to have any effect. In a multiple measurement system using a full bridge, interaction is not a problem. Interaction problem can inadvertently be introduced when using a low level half bridge system by introducing a potential common impedance during noise suppression. In resolving noise problem, a designer usually finds it very convenient and effective to place a large capacitor across each of the bridge outputs for minimizing unwanted noise voltages. A cursory circuit analysis of Figure 3.4.7-1 will show that if the thermometer element is open-circuited intermittently, the noise suppression capacitor placed across the bridge output would charge and discharge, and thus interact with each of the bridge output capacitors. Thus, if a thermometer element is open-circuited intermittently, the capacitor for this bridge would react as a common impedance. This is not easily recognizable because



Test method for determining potential noise injection points in temperature measuring system.

Figure 3.4.7-2

a failure in the thermometer must occur before interaction can take place. Therefore, when using capacitors for resolving noise problems, various failure modes in the system should be simulated for cause-effect before the design becomes finalized.

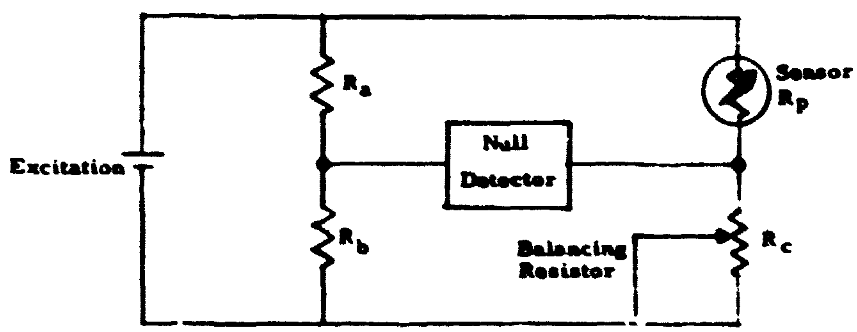
3.4.9 Reactance

Reactance can be a problem in either full or half bridge system where a fast response time is desirable. Designers normally would consider only the response time of a thermometer relative to some sudden thermal change. However, if a reasonable response is desirable, designer should analyze the total reactance of a system which should include thermometer, cable capacitance, connector contact inductances, and capacitance/inductance in the bridge circuit. Usually, thermometer and bridge reactances can be evaluated on a bench level test; and thereby, response time can be determined. However, in a large vehicle system, cable capacitance and inductance may be considerable. A helpful figure for capacitance and inductance is usually 6,000 pico-farads per foot, and 20 nano-henries per inch (MHZ range) for a 20 gage (AWG) shielded twisted wire. Cable and connector inductances may not be a problem since the basic response time is limited by the thermometer in the total system. Usually, the detrimental reactance is introduced inadvertently when capacitors are introduced during noise suppression. The RC time constant of these capacitors could be considerable to affect the overall system response. The response time should match that of the thermometer.

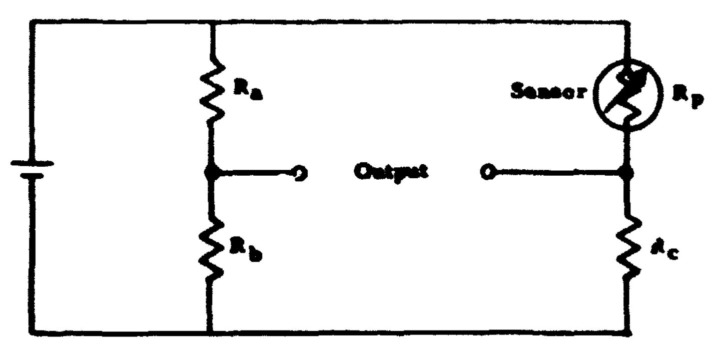
In conclusion, when design considerations are evaluated during design of temperature measurement system, a check list of all design considerations should be prepared (see Table 3.4.9-1). In this manner, each time a change is made for one consideration, a check list should direct the designer to a potential problem in another design consideration. Therefore, a reasonable tradeoff can be obtained for optimum finalized design. It should be noted here that there are other design considerations, particularly where ac instead of dc excitation is used. However, above design considerations discussed indicate the complexity of a simple looking bridge design.

Since 1871, when Sir William Seimens described the first resistance thermometer, numerous bridges have been developed such that a great confusion presently exists when selecting a suitable bridge. It is hoped that this report would eliminate that confusion and enable a designer considering a large temperature measuring system design to methodically select a suitable bridge scheme.

All bridges can be classed in their basic form as either a full bridge or a half bridge. These bridges are then described as either symmetric or asymmetric. Figures 3.4-1 and 3.4-2 depict a full bridge and a half bridge with condition specified for its use as a symmetric or an asymmetric. These bridges are then balanced or unbalanced depending on a particular usage (see Figure 3.4.9-1). Therefore, these basic bridges can be categorized into eight different types or methods. Table 3.4.9-1 depicts evaluation of each method relative to a major design consideration. It should be noted that the effects could change depending upon the use of the basic bridge as a low level or high level output system. Variations added to these ten types of



Balanced Full Bridge Circuit



Unbalanced Full Bridge

Typical Balanced and Unbalanced Full Bridge Circuits

Figure 3.4.9-1

Table 3.4.9-1. Design Guide - Temperature Measurement System

WHEN CONSIDERING DESIGN CONSIDERATION / AFFECTS DESIGN CONSIDERATION	LEAD WIRE R	LINEARITY	NOISE	SENSITIVITY	INTERACTION	ACCURACY	RESPONSE	THERMOELECTRIC EMF
LEAD WIRE R	-	YES	YES	YES	NO	YES	NO	NO
LINEARITY	YES	-	NO	YES	NO	YES	NO	NO
NOISE	YES	YES	-	NO	YES	YES	YES	YES
INTERACTION	YES	NO	YES	NO	-	YES	YES	YES
SENSITIVITY	YES	YES	YES	-	NO	NO	NO	NO
ACCURACY	YES	NO	YES	NO	YES	-	YES	YES
RESPONSE	NO	NO	YES	NO	YES	YES	-	NO
THERMOELECTRIC EMF	NO	NO	YES	NO	YES	YES	YES	-
SELF-HEATING	YES	NO	NO	YES	NO	YES	NO	NO

bridges have been due to various solutions in resolving the lead resistance problem. Most of these variation bridges have been named in accordance with the developer, e.g., Callendar-Griffiths bridge, Mueller bridge, and Seimen's three or four wire bridges. Leadwire resistance has been the most troublesome problem in designing a temperature measuring system. Therefore, after having selected a basic type of bridge, careful evaluation of the various types of variations of the basic bridges such as Seimen's, Smith's and Mueller's, all of which appear to be very popular for leadwire resistance suppression, should be made. For example, Mueller uses a full bridge system with added circuitry for compensation of leadwire resistances which can be modified for use in a half bridge scheme.

Question now arises as to which type of a basic bridge should be used: should it be a full bridge or a half bridge, should the bridge be designed as an asymmetric or a symmetric full or half bridge, and should it be operated as a low level bridge output or a high level bridge output, and finally, should it be balanced or unbalanced. Table 3.4.9-2 may provide some direction when making this decision. It should be noted that for all eight bridges, certain design considerations are all common, such as lead resistance, reactance, and thermoelectric problems. When using Table 3.4.9-2, low level and high level outputs should be considered, e.g., importance in power limitation which is usually the determining consideration in a bridge design, especially in cryogenic usage where resistance of a thermometer element is quite low, can be minimized by use of low level system.

A typical example for designing a temperature measurement system can best illustrate the problems encountered in the design approach. An asymmetric half bridge is favored for this example based on the results of Table 3.4.9-2 for a platinum thermometer with a range in the cryogenic region. It is noted that the thermometer resistance in the cryogenic region is very small and therefore self heating in the thermometer element is critical. The following advantages gained by use of asymmetric half bridge are discussed with some comparisons made between full and half symmetric bridges.

3.4.10 Sensitivity

For a maximum sensitivity, it is desired that the thermometer be energized with its maximum allowable voltage. For example, if this voltage is 5 volts, and if k = 10 (see Figure 3.4.10-1), then the power supply for the full bridge can be 5[?] volts without exceeding the sensor limitation. The bridge arms divide this supply so that 5 volts appear across the sensor, and 50 volts across the KR arms. A half bridge can also have the same voltages by using one 5-volt source and one 50-volt source. Figure 3.4.10-1 depicts the voltage change that appears across Rg for full or half bridges when sensor changes by one percent, if Rg has no load. As k varies from 1 to 50, the bridge output voltage changes by a fact . of nearly 2. Both the full bridge and the half bridge sensitivities . . on the sensitivity graph have the same no-load voltage signal, and th. :fore are shown as an ideal condition. This means that when a load is applied, the sensitivity would decrease by the mount of the load resistance applied across the bridge output.

Table 3.4.[illegible]-2. Basic Bridge Comparison

BASIC BRIDGE TYPES / DESIGN CONSIDERATIONS	SENSITIVITY	LINEARITY	OUTPUT POWER	INTERACTION	POWER LIMITATION	OUTPUT IMPEDANCE
1. FULL BRIDGE SYMMETRICAL BALANCED	GOOD	EXCELLENT	POOR	FAIR	FAIR	LARGE
2. FULL BRIDGE SYMMETRICAL UNBALANCED	POOR	FAIR	FAIR	FAIR	GOOD	LARGE
3. FULL BRIDGE ASYMMETRICAL BALANCED	GOOD	EXCELLENT	GOOD	FAIR	GOOD	LARGE
4. FULL BRIDGE ASYMMETRICAL UNBALANCED	GOOD	EXCELLENT	GOOD	FAIR	GOOD	LARGE
5. HALF BRIDGE SYMMETRICAL BALANCED	FAIR	GOOD	FAIR	EXCELLENT	GOOD	LOWER
6. HALF BRIDGE SYMMETRICAL UNBALANCED	FAIR	FAIR	FAIR	EXCELLENT	GOOD	LOWER
7. HALF BRIDGE ASYMMETRICAL UNBALANCED	EXCELLENT	GOOD	EXCELLENT	EXCELLENT	EXCELLENT	LOWER
8. HALF BRIDGE ASYMMETRICAL BALANCED	EXCELLENT	EXCELLENT	EXCELLENT	EXCELLENT	EXCELLENT	LOWER

3.4.11 Power Requirements

When the bridges are loaded, Rg is not infinite, power output becomes a factor. Figure 3.4.10-1 depicts that a half bridge is significantly better. The half bridge offers lower output impedance and thus greater output power can be attained. A loaded asymmetric half bridge with k = 20 can produce four times the power output of a symmetric full bridge with k = 1. Therefore, power advantage can be attained if half bridge is used over a full bridge and also used as an asymmetric rather than a symmetric bridge. Usually, a factor of 2 as depicted in Figure 3.4.11-1 can be obtained by use of asymmetric half bridge. The power requirements of the asymmetric bridge and the power dissipated in the dummy arm usually establish the k factor value selected for the bridge. A k factor of 20 approximates the knee of the power-voltage gain curve (see Figure 3.4.10-1). This, or a higher value, is desirable but not always practical. In many cases, a high active leg potential voltage is not required. One volt is used for many temperature bridges to limit dissipation in the temperature sensor. For example, with one volt across a sensor, it will dissipate 10 milliwatts and the KR dummy load will dissipate 200 milliwatts at k = 20 with KE at 20 volts. It should be noted that 10 milliwatts is the maximum power limitation imposed by most thermometer manufacturers.

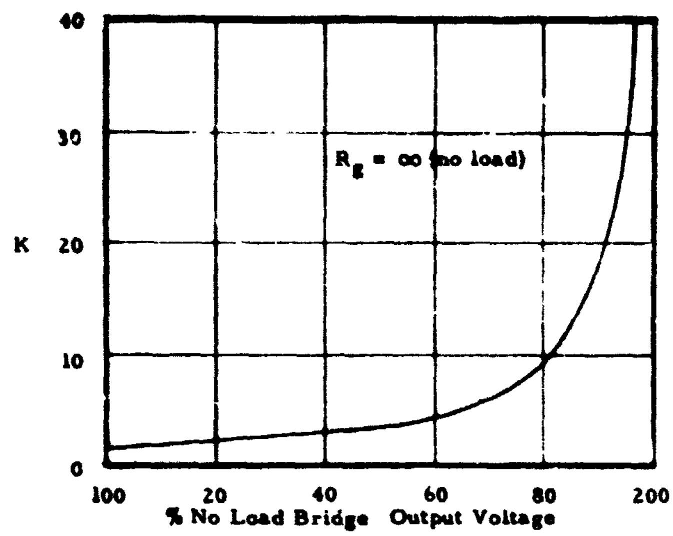
3.4.12 Linearity

Figure 3.4.12-1 depicts the linearity of a half bridge with no load (Rg is infinite) is improved as k is increased from 1 to 20. The asymmetric full or half bridge is capable of increased linearity because the current flow through the active arm is at high asymmetric ratios effectively independent of its resistance. In a symmetric bridge this cannot be attained. Therefore, linearity of the asymmetric full or half bridge is considered far superior for all conditions of loading and with narrow or wide excursion of the active-arm resistance. However, when a null reading is employed in any type of bridge, linearity is not a significant problem. Bridge linearity under load can also be improved if the bridge is so designed that the active sensor decreases in resistance rather than increases (see Figure 3.4.10-1).

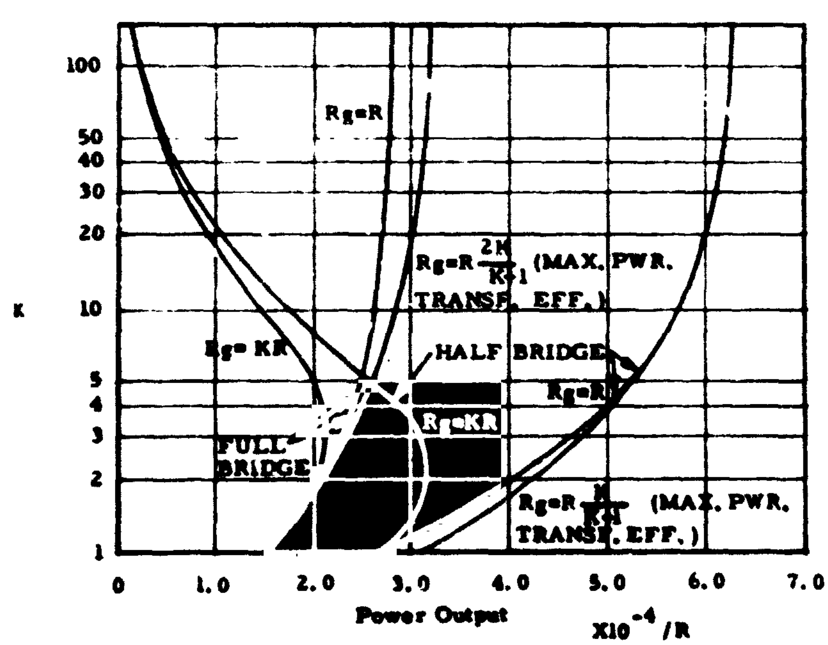
3.4.13 Miscellaneous Advantages

The half bridge has other important advantages such as (1) wiring is reduced, (2) power-consuming dummy legs are eliminated, (3) the center tap of the split power supply source may be grounded. This allows multiple bridges to operate from one common power supply without serious interaction. Also, this is essential to telemetry applications where all outputs have to work against ground. With full bridges, differential input commutation is required to secure the same advantage where multiple bridges are powered by one excitation source.

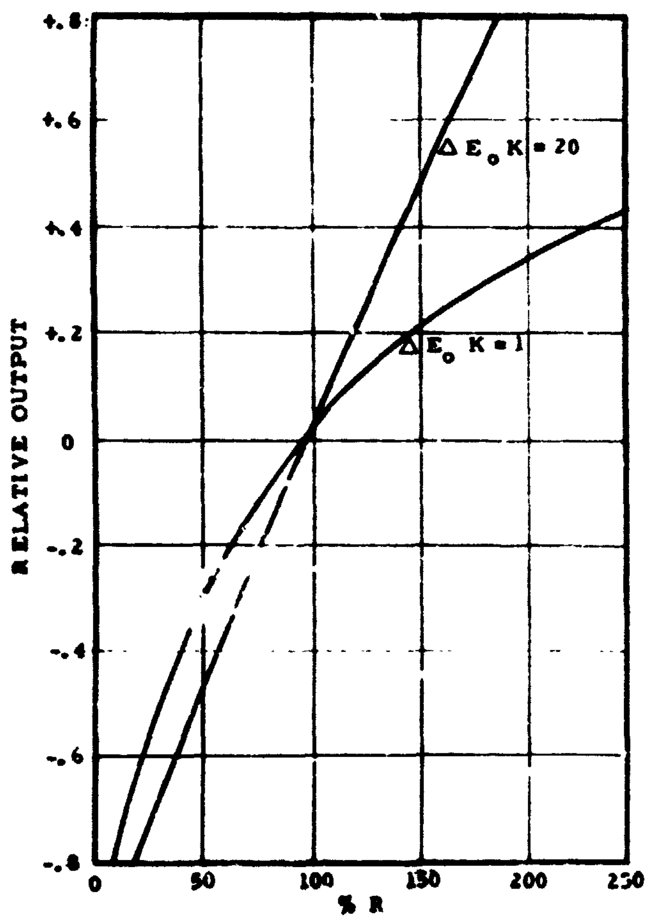
The limitation of the asymmetric bridge is expressed in terms of (1) variations of active-arm resistance, (2) desired linearity, and (3) reasonable value of asymmetric-leg potential. Power dissipation in the asymmetric-leg and power-supply wattage requirements should be considered. Aside from these limitations, an asymmetric half bridge appears to be far superior in performance



As K Varies from 1 to 50 The Output Voltage of Full or Half Bridge Changes by a Factor of 2



Bridge Output Characteristics
Figure 3.4.10-1



Bridge Linearity Characteristics

Figure 3.4.11-1

over all other basic types of bridges. It should be noted here that two precautions must be considered when employing the half bridge. The first precaution: Rp must be large relative to any lead wire resistance to prevent errors due to the variations of leadwire resistance with temperature. A second precaution: if, through any cause, the power supply outputs do not change in the same proportion, then a fraction of the difference of the absolute values of their voltages will appear as an output voltage; and this is especially critical where low level output is used.

Since lead resistance problem appears to be common and outstanding with either full or half bridge methods, a brief discussion of the various bridges developed for the purpose of correcting this problem may be useful. From this, further variations can be adapted for use in either full or half bridge method selected for a particular leadwire resistance problem encountered.

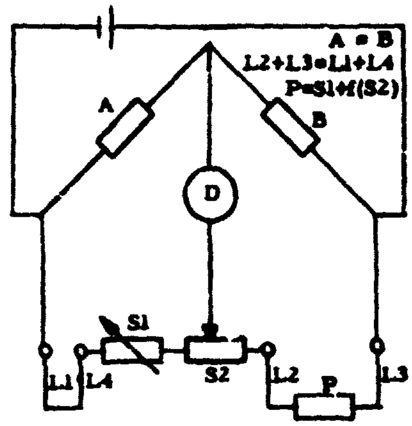
3.4.14 Callendar-Griffith's Bridge (see Figure 3.4.14-1)

The Callendar bridge was designed for compensation of lead resistance problem. This bridge provides a compensating loop of wire which essentially duplicated the leads to the thermometer in terms of electrical properties and physical location. This loop was then placed in an adjacent arm of a unity-ratio bridge. This bridge permits the use of a potentiometer for the finest balance setting.

The Callendar bridge is considered good for use where temperature difference measurements are required. This type bridge also has advantage over the 3-wire types in that the contact resistance of the null potentiometer is placed in series with the bridge output and thus may be neglected. By eliminating the effect of lead wires and contact resistance, the bridge is useful when the thermometer element resistance is low - from 10 to 100 ohms. However, this type bridge is not considered good for use where precise measurement is desired.

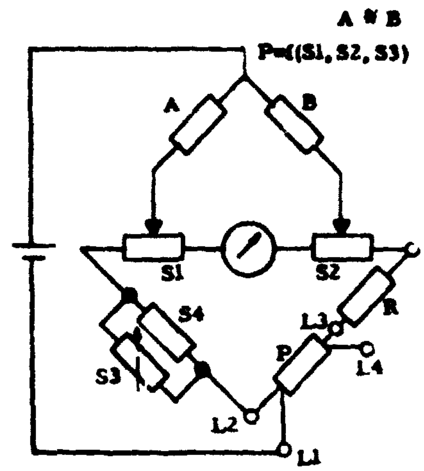
3.4.15 Mueller Bridge (see Figure 3.4.15-1)

This bridge is a variation of the Wheatstone Bridge. Various advantages can be gained by this bridge such as the use of unity ratio arms which permits thermometer lead compensation by lead balance and/or reversal techniques which are used to compensate for small differences in the ratio arms. The unity ratio also permits a simple means of inferring the thermometer current by measuring the bridge supply current. The bridge also can reduce the effects of resistance variation in switch contacts associated with the calibrated variable arm of the bridge. Thus, this bridge can be effective in eliminating thermoelectric emf where this is a problem. To eliminate the effect of thermoelectric emf's, the bridge is normally balanced by setting the variable arm so that the indication of the null detector is unchanged when the bridge current is reversed. This also provides the advantage of doubling the output voltage swing of the bridge for a given thermometer current and degree of unbalance. Commercial forms of this type bridge are available which permit measurements of resistance up to the order of 400 ohms with the smallest discrete step representing changes of one micro-ohm. The Mueller bridge provides exact compensation for lead resistance and ratio arm unbalance without significant demands on current stability.



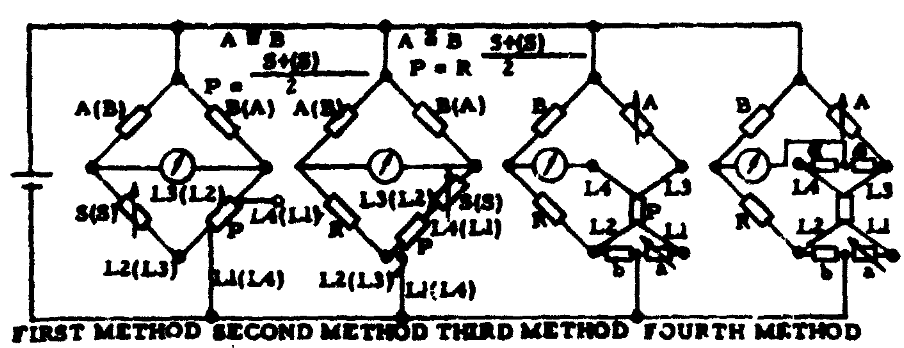
The Callendar-Griffiths Bridge

Figure 3.4.14-1



The Mueller Bridge

Figure 3.4.15-1



The Smith's Bridge

Figure 3.4.16-1

An important disadvantage with this bridge is a stringent requirement of low and constant internal switch contact resistance which must be maintained. If switching among thermometers is required, an external switch with very stable contact resistance must be provided.

3.4.16 Smith Type III Bridge (see Figure 3.4.16-1)

In 1912, F. E. Smith proposed four bridge configurations for resistance thermometry. Of the four, only Smith's third method survives as a widely accepted bridge. This method has a calibrated variable arm typically 100 times as large as the thermometer resistance, so that the need for switch contact resistance stability is greatly reduced. The effect of thermometer lead resistance difference is reduced by use of an auxiliary calibrated variable set of resistances. Smith III bridge is outstanding in the reduction of switch stability requirements. Also, it is noted for reduction of lead resistance effects without the requirements for a double bridge balance and the need of averaging calculation.

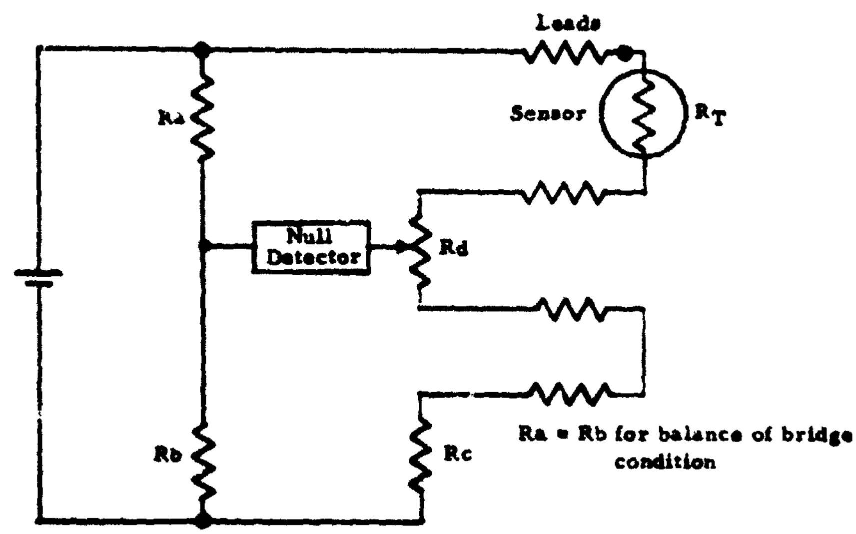
Some of the disadvantages associated with this bridge are as follows: (1) the balance equation of the bridge is complicated, and some error is introduced by both the unbalance and the magnitude of lead resistance, and (2) the need for stable resistors of larger value (usually 1000 ohms or greater) and accompanying requirements for better insulation resistance under some conditions can become a factor.

3.4.17 Balanced Three-Wire and Four-Wire Bridge (see Figure 3.4.17-1)

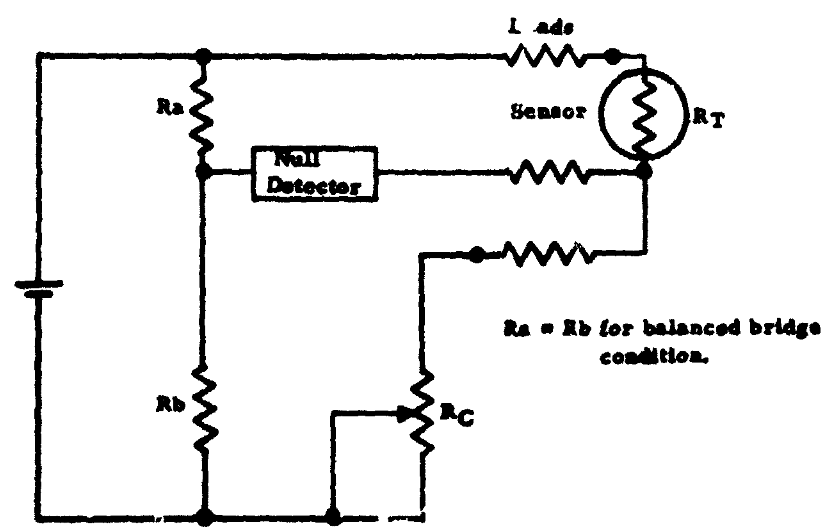
These bridges are in balance when the sensor arm has the same resistance as the adjacent arm; therefore, the same amount of lead resistance does not affect the balance point, provided the lead resistances are equal. Although the bridge shown is a full bridge, the same principle can be applied to a half bridge. The basic advantage of this type is that its linearity is not a problem due to measurement beginning at null point. Its disadvantage is that lead wires must be equal.

3.4.18 Seimens' Three and Four-Wire Bridges (see Figure 3.4.18-1)

The three-wire bridge was conceived by W. Seimens in 1871 as a means for eliminating the effect of leadwire resistance in the null. A rheostat is generally placed in series with the thermometer to null the bridge. However, variations in the contact resistance of the rheostat upsets the bridge null which limits the bridge usefulness to relatively high thermometer elements. This is due to the null being a function of leadwire resistance and of variations in the resistance. The 4-wire bridge is a variation of the bridge with four-wire compensation. Similar to the three-wire case, variations in leadwire resistance are distributed equally in both arms and thus do not affect the bridge null.

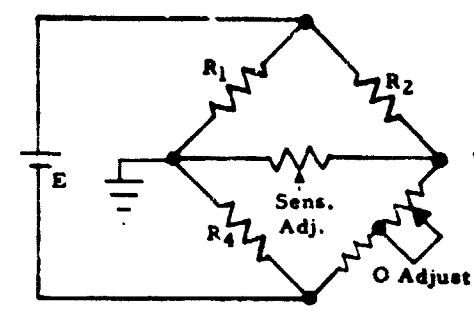


Balanced Four-Wire Bridge

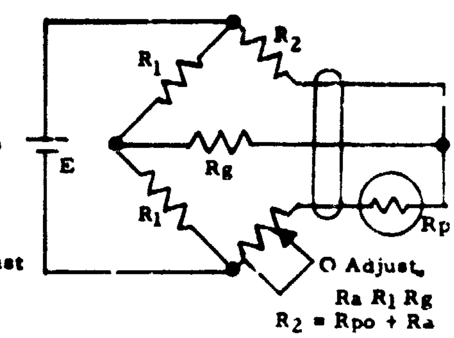


Balanced Three-Wire Bridge

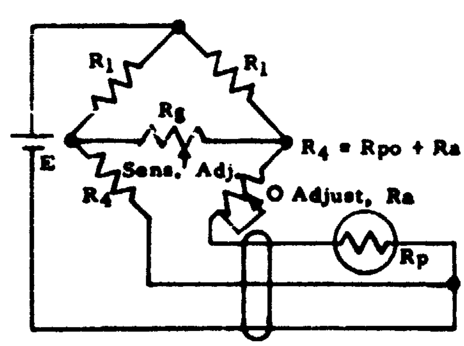
Figure 3.4.17-1



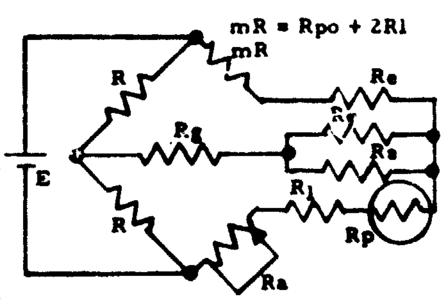
a. A Full Bridge With Zero and Sensitivity Adjustments



b. Siemans 3 Wire Bridge



c. A Variation on the Siemans 3 Wire Bridge



d. A Four Wire Bridge

Examples of Full Bridges

Figure 3.4.18-1

3.4.19 L&N Direct-Reading Bridge (see Figure 3.4.20-1)

This circuit uses a calibrated variable arm composed of a fixed resistance paralleled by a variable resistance. The relation of thermometer resistance to absolute temperature is not a linear one, but is generally described by quadratic formulas. Therefore, by the paralleling arrangement, a quadratic relationship between the bridge output setting and the resistance of the bridge can be obtained to match the thermometer characteristics.

3.4.20 Slidewire Bridge (see Figure 3.4.20-1)

The use of potential dividing slidewires for linear measurement of resistance avoids the problem of absolute adjustment and contact resistance due to use of slidewires as rheostats. Two ganged slidewires are used in this bridge with one compensating the potential upset of ratio by the other. The major disadvantage in this type system is that a mechanical device is required for balancing the bridge.

3.4.21 Stull Bridge (see Figure 3.4.20-1)

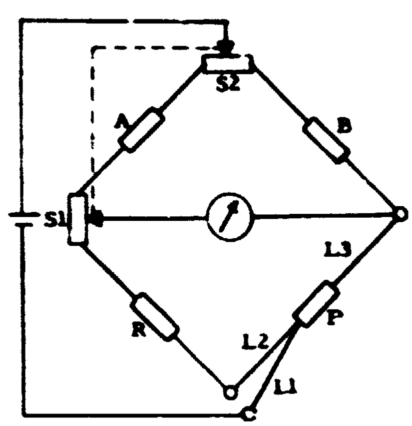
This bridge uses slidewire principle, combined with some of the Mueller bridge arrangements. This bridge has a span of 1.0 ohm and has a capability of a range from 0 to 190 ohms with 0.001 ohm resolution.

3.4.22 Triple Bridge - Rosemont (REC) (see Figure 3.4.22-1)

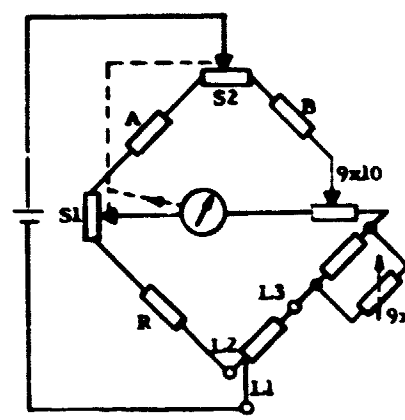
Basically, this bridge resembles a Kelvin bridge with an inner Kelvin bridge (Kelvin double bridge). This bridge makes use of the ratio of output voltage to excitation voltage for the purpose of measuring sensor resistance. It suppresses leadwire resistances effectively, whether or not they are equal because of the provision for adjustment of zero and slope of the output. Errors due to lead resistance are typically reduced by a factor greater than 100, as compared to the ordinary three-wire bridge when leads are not equal. Bridge unbalance and nonlinearity can be negligible or can be made relatively large in cases where this is desirable. Thus, control of bridge unbalance nonlinearity can be used for cancellation of nonlinearity due to thermometer element metal. It should be noted that the mathematical analysis of this bridge is very complex. However, a laboratory breadboard analysis of this bridge would be beneficial in fully appreciating the unique features described.

3.4.23 Conclusion

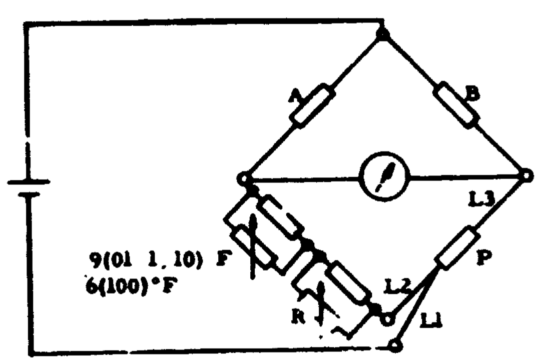
There are many other types of dc bridges not listed in this report. However, in most of these, variations may be for leadwire resistance compensations. Laboratory breadboard of some of the bridges discussed here would be worthwhile when making a variation to the selected basic bridge design, particularly where a full understanding and appreciation of problems related to a complete bridge design are desired. Furthermore, a complete mockup of a finalized temperature measurement system is recommended for a complete failure mode analysis. There are certain fundamentals common to all methods, such as half or full bridge, asymmetric or symmetric, balanced or unbalanced, and low or high level output, which determine the quality of measurement which can be made.



Ganged slidewires keep ratio constant in Leed's slidewire bridge.

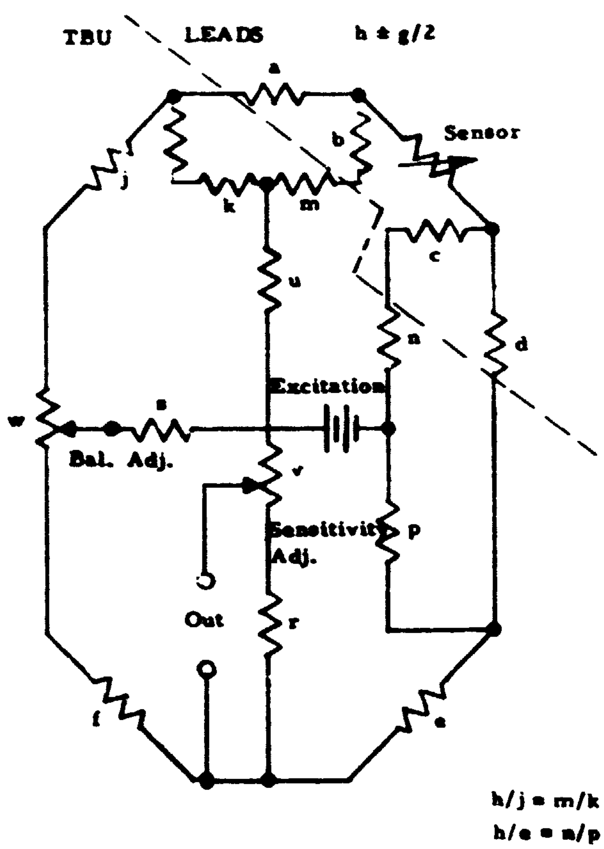


Stull recorder uses slidewire principles in automated bridge.



A linear variable resistor shunted by a fixed resistor approximates the quadratic temperature-resistance curve of a resistance thermometer for direct reading.
L&N Dir ct-Reading Bridge

Figure 3.4.20-1



Triple Bridge Rosemont Sensor

Figure 3.4.22-1

To this, variations are added based on optimum considerations to the design considerations. The various bridges discussed here can be best summarized by use of a table (see Table 3.4.23-1) for comparison and analysis when selecting a particular measurement method. As a general guide, when selecting a method among the two regarded as the most popular methods (Mueller and Smith Type III), some design criteria for selecting are given as follows:

Mueller bridge is recommended wh e (1) high precision is required, (2) resistance to be measured does not exceed 450 ohms, and (3) lead resistances do not change significantly between balances.

Smith Type III bridge is recommended where (1) resistance to be measured does not exceed 150 ohms, (2) lead resistance is not largely or greatly unbalanced, but may vary considerably between balances, and (3) lead resistance is large and/or greatly unbalanced and/or rapidly varying.

3.5 SURVEY RESULTS

Temperature transducer manufacturers responding to the survey were:

ACCO Bristol	Genisco
AMC Electronics	Hy-Cal Engineering
American Standard	Honeywell
Bell & Howell	RdF
Dynasciences	Rosemount
Foxboro	Trans-Sonics
General Electric	Victory Engineering

This list falls far short of covering all temperature transducer manufacturers, but does include some of the nation's leading temperature transducer suppliers. Of the manufacturers listed, only a few supply both probe and surface type transducers for cryogenic application. In addition, all of the suppliers listed have engineering and manufacturing capability of building transducers which meet specialized requirements. This survey is intended to provide knowledge of manufacturer's capability in the temperature transducer field rather than to provide a list of parts available for space u e

Generally for space applications, program requirements are s ensive that off-the-shelf equipment seldom satisfies all requirements. S of these requirements include such basic items as material and subcomponent standards, such as lubricants, wire types, and resistors; fabrication procedures such as soldering and welding specifications; and quality control inspection requirements. Equipment acceptance tests and qualification programs and end item c subcomponent traceability are other common requirements.

Probe type units are manufactured as open elements (sense wires exposed to the measured fluid) or closed elements (sense wires encased in a housing). For liquid oxygen and liquid hydrogen applications, only the closed element designs are applicable. Surface type transducers are manufactured in a variety of sizes and shapes designed for attachment by cementing welding or clamping. In general, these transducers are not designed for immersion in LOX

Table 3.4.23-1. Factors in Selecting a Measurement Method For Leadwire Resistance Compensation

FACTOR	CALENDAR GRIFFITHS	SIEMENS	KELVIN DOUBLE (TRIPLE BRIDGE)	SMITH TYPE III	MUELLER
RANGE (OHMS)	0 - 1,111	0 - 1,111	0 - 1,111	5 - 100	0 - 422
RESOLUTION ( )	1000	1000	100 (rp 100) 1000 (Rp 100)	10	1
LEADS-NUMBER	4	3 OR 4	4	4	4
LEAD RESISTANCE	MUST BE EQUAL	MUST BE EQUAL	BALANCE OPERATIONS PROVIDE LEAD COMPENSATION	EFFECT SUPPRESSED	BALANCE OPERATIONS PROVIDE LEAD COMPENSATION
POWER SUPPLY STABILITY	NOT CRITICAL	NOT CRITICAL	NOT CRITICAL	NOT CRITICAL	NOT CRITICAL
INTERNAL SWITCH STABILITY-EMF	CRITICAL	CRITICAL	IMPORTANT	IMPORTANT	CRITICAL
SENSOR SELECT SWITCH STABILITY EMF-MULTIPLEXING	CRITICAL	CRITICAL	SUPPRESSED EFFECT	SUPPRESSED EFFECT	CRITICAL
RANGE (K)	20K to 630K	20K to 630K	20K to 630K	77K to 630K	20K to 630K

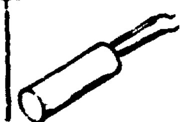
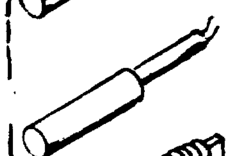
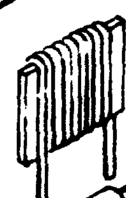
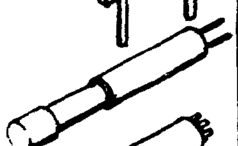
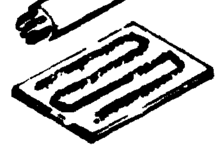
or LH_2 but are designed to operate at the cryogenic temperatures in a gas environment. The limiting factor for direct contact with the liquid is the construction material and the lack of a hermetic seal.

Common probe resistances advertised in the brochures are 1380, 1400, and 1256 ohms at the ice point. Other resistance values are advertised as available on special order.

Table 3.5-1 summarizes the element types used by most manufacturers in producing probes and surface transducers for cryogenic usage.

[illegible]

[illegible]

TYPE NO.	CONFIGURATION	CONSTRUCTION	APPLICATIONS	TEMPERATURE RANGE	RESISTANCE RANGE
1		Platinum wire, wound on a ceramic insulated platinum rhodium mandrel. Glass type waterproof outer coating. Platinum leads in MgO insulated swaged stainless steel tubes.	Cryogenic to mid range temperature measurement, usually in open type construction for fast time response.	-435 to +500°F Will operate -452 to +1000°F	Up to 8000
2		Platinum wire wound on a ceramic insulated platinum rhodium mandrel. Cermaic outer coating.	Cryogenic to mid range temperatures. Always mounted in a sealed cartridge. High Precision applications.	-435 to +500°F	Up to 8000
3		Platinum or nickel wire wound on mica. Leads brought off platinum ribbons.	Surface temperature measurement.	-435 to +1000°F	Up to 2000
4		Platinum, nickel or Balco wire wound on a high purity Al_2O_3 mandrel. Platinum or nickel lead wires.	Wide range, low cost, environmental resistant. Available open or sealed construction.	-435 to +1800°F	Up to 2000
[illegible]		Platinum wire in Al_2O_3 Tubes cast in gold.	Highest stability.	-435 to +1300°F	Up to 25
6		Platinum wire coil cemented to a plate.	Surface temperature measurement.	-435 to +1000°F	Up to 1400

4.0 HIGH TEMPERATURE STRAIN GAGES

4.1 INTRODUCTION

Although strain measuring techniques have progressed rapidly since the development of the first strain gage, the requirements for their use have advanced much faster. This situation is especially true for obtaining flight load measurements on high speed vehicles operating in the earth's atmosphere. The aerodynamic heating associated with these high speed vehicles can be a major cause of strain gage error. Figure 4.1-1 gives the temperature profile on an assumed Mach 6 vehicle operating at 90,000 feet. A review of the figure shows temperatures up to 1800 F on aerodynamic surfaces. Strain gage output due to thermal stresses at these high temperatures can produce load measurement errors greater than these due to gage performance characteristics. To obtain accurate flight load measurements, these errors must be eliminated in the strain gage design.

4.1.1 Strain Gage Requirements

The objective of this section of the Measurement Components Technology report is to review various strain sensing devices and evaluate their performance in a 150 to 2000 F thermal environment. The evaluation includes gage principle of operation, gage materials, gage attach methods, installation techniques and gage availability. The section does not include signal conditioning or data-acquisition equipment.

4.1.2 Definition of Terms

The following is a listing of definition of terms used in conjunction with strain gage applications.

Strain - Fractional change in leng[illegible] ...used by uni-axial stress [illegible] direction of gage axis. $\frac{\Delta L}{L} = \epsilon$, a value o[illegible] ϵ = 1 X 10^{-6} is called [illegible] strain.

Stress - The internally distributed forces within a body which [illegible] to resist deformation. The dimensions of stress are force per unit area. Stress is proportional to strain $\frac{F}{A} = E\epsilon$ where E is Young's modulus of elasticity.

Gage Factor - A measure of gage sensitivity. The fractional change in resistance of the mounted gage divided by the fractional change in length (the strain) of the surface upon which it is mounted caused by a uni-axial stress in the direction of the gage axis.

$$GF = \frac{\Delta R}{R} \Big/ \frac{\Delta L}{L} = \frac{\Delta R}{R} \Big/ \epsilon$$

R = original gage resistance
L = original length of surface upon which gage is mounted
ϵ = strain

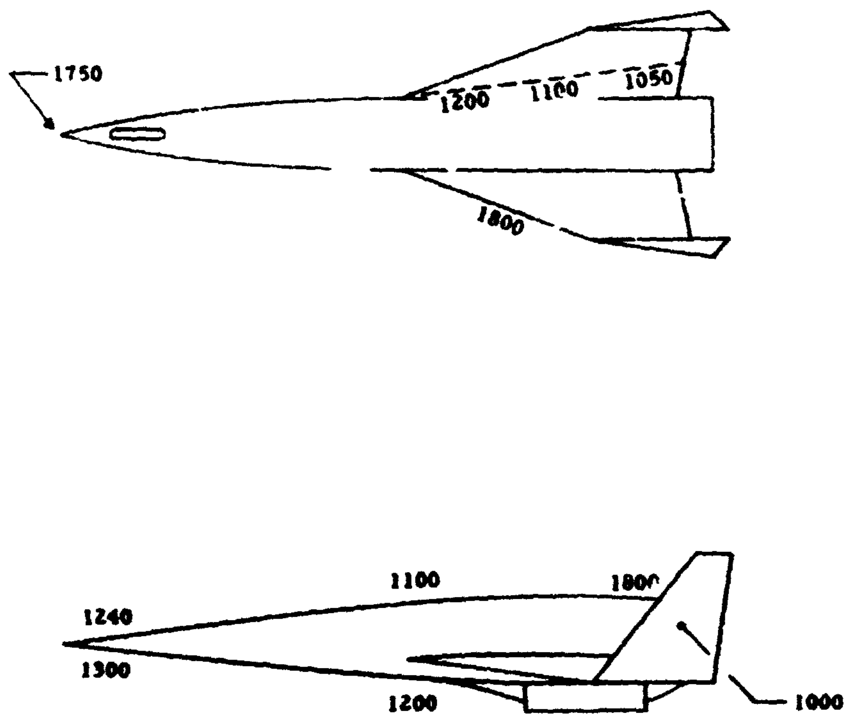


Figure 4.1-1 Surface Temperatures (F) of Assumed Mach 6 Vehicle

Apparent Strain - The change in resistance of a mounted strain gage ($\frac{\Delta R}{R}$) due to a change in temperature without an applied load on the specimen. Apparent strain is due to the combined effects of differential thermal expansion and the thermal coefficient of resistivity of the strain wire alloy.

Differential Thermal Expansion - The effect which occurs when the strain wire element and the specimen on which it is mounted have different expansion rates with temperature. This phenomenon places the strain element in either compression or tension with no applied load to the specimen.

Coefficient of Thermal Resistivity - All strain wire filaments exhibit a change in electrical resistance with temperature changes. The rate of change of resistance with temperature is defined as the coefficient of thermal resistivity. This coefficient of resistivity can be adjusted by heat treating in the case of certain nickel - chrome alloy wires.

Active Gage Length - The distance over which the strain gage, when mounted on a surface, will measure the strain undergone by that surface.

Strain Range - The allowable percentage elongation of a strain gage. It is a function of the degree and anneal of the strain sensing element, the elastic properties of the carrier, and the properties of the bonding agent.

4.2 HIGH TEMPERATURE STRAIN SENSING DEVICES

A literature survey was conducted to select strain sensing devices which have potential application in a 1500 F to 2000 F thermal environment. The following devices were selected as a result of this survey:

a. Electrical resistance strain gage

b. Electrical capacitance strain gage

c. Thermal - null strain sensor

This report contains an evaluation of the above devices as derived from the literature survey.

4.3 ELECTRICAL RESISTANCE STRAIN GAGE

Since its conception in the late 1930's, the bonded filament resistance strain gage has been the primary method of measuring the magnitude of strain due to stress. The resistance strain gage operates on the principle that when a load is applied on any material, that material will expand or contract causing strain within the material. If a grid of wire is bonded to the material, it will stretch or be strained exactly as the surface of the test material is strained. This stretching and compressing of the grid wire causes a change in the electrical resistance of the wire which is proportional to the strain in the test member. When a wheatstone bridge circuit is set up so that the only source of unbalance is due to the change of resistance in the strain gage grid wire, due to the application of strain on the gage, the difference in potential across the output terminals becomes a measure of strain.

4.3.1 Resistance Gage Requirements

The requirements for resistance strain gages used in high temperature applications should include the following:

a. Both the gages and their attachments must withstand the thermal environment, without degradation, for the life of the test program.

b. The gages must be precisely and uniformly compensated for the thermal expansion of the material to which they are attached.

c. The gages must withstand repeated combinations of temperature and total strain for a long period of time.

d. The gages should have a high gage factor to yield maximum signal from a given strain.

e. The gage factor should have a small and predictable variation with temperature.

f. The gage should dissipate the heat resulting from bridge excitation voltage without excessive self-heating in order to generate a maximum signal.

g. The gage should have drift characteristics that are small when compared with the output from the measured load.

h. The gage and its attachment must maintain a high resistance to ground during and after repeated exposure to high temperature.

i. The gage should be easily and quickly installed.

4.3.2 Resistance Strain Gage User Requirements

In addition to information supplied by gage manufacturers, independent evaluations of gages should be made depending upon their intended usage. Such evaluations aid in selecting the best available gage for a particular application and making the best use of the selected gage. Some of the users requirements and gage properties that should be considered when evaluating gage selections are:

a. Temperature Range

b. Anticipated Strain Levels

c. Duration of Test Program

d. Material on Which Gage Will be Mounted

e. Space and Wire Routing Restrictions

f. Type of Load to be Measured

g. Number of Measurements Required

h. Compatibility with Data-Acquisition System

i. Time Available for Installation

4.3.3 Resistance Strain Gage Property Considerations

In selecting a resistance strain gage for high temperature applications, the following gage properties should be considered:

a. Useful Temperature Range

b. Apparent Strain and Scatter in Apparent Strain

c. Maximum Excitation Voltage

d. Method of Attachment

e. Gage Factor and Gage-Factor Variation with Temperature

f. Drift Characteristics

g. Fatigue Characteristics

h. Gage Resistance

i. Effect of High Heating Rates

Some of the items on the above list are essential, while others are only desirable. It is essential that the elevated temperature and heating rates do not alter the characteristics of the gage to the extent that meaningless data are obtained.

4.3.4 Temperature Compensation

One of the major contributors to errors in high temperature strain gage measurements is effects of apparent strain. In an effort to reduce the thermal apparent strain of resistance strain gages, temperature compensation is included in the designs. For high temperature strain gage applications, two methods of temperature compensation are commonly used. These methods are "selected melt" gage design and the "active-dummy" gage design.

4.3.4.1 Selected Melt Gages

The elements of selected melt gages are fabricated of alloys which are specially treated to a specified temperature coefficient of resistance as required to correspond to the thermal coefficient of expansion of the material on which the gage is installed. The element is termed "self compensating" and should exhibit a small thermal apparent strain when used properly.

4.3.4.2 Active-Dummy Gages

The oldest method of compensating for temperature-induced errors in strain measurements is by utilizing dummy and active gages. The principle used is quite simple. An active gage is bonded to the test specimen and a second dummy gage is bonded to an unstressed tab or block of the same material as the test specimen. These gages are connected to adjacent arms of wheatstone bridge. In this configuration the dummy gage cancels out the effect of temperature changes on the resistance of the active gage and bridge balance will respond only to mechanical strains on the active gage. The inaccuracies in this method are due to the difficulty in finding an absolute strain-free area for location of the dummy gage and locating both gages such that they will be subjected to identical temperatures.

The active dummy gage system compensates for the errors caused by the resistance change in the gage elements due to temperature changes. It does not compensate for errors caused by the differential thermal expansion which occurs between the gage elements and the material on which the gage is mounted. This portion of the "apparent strain" can be eliminated by the addition of a compensating resistor (Rtc) in series with the active gage in the bridge circuit. The value for Rtc may be determined by using the following equation:

$$R_{TC} = \left(\frac{\alpha_{eg} \quad \alpha_{es}}{\alpha_{r}} \right) R_g$$

where α_{eg} = coefficient of expansion of the gage

α_{es} = coefficient of expansion of the specimen

R_g = gage resistance

α_r = temperature coefficient of resistivity of the gage element.

4.3.5 Sensing Element Materials

Because the change of resistance in the sensing element indicates the measure of strain, the choice of element material is extremely important. The materials used for electrical resistance strain gage sensing elements are divided into two groups: metallic and semiconductor. Strain gages made of semiconductor material are very sensitive to temperature changes and exhibit extreme non linearity at high temperature. Because of these adverse temperature characteristics, they are not used for airborne application and are eliminated from further discussion in this report.

In an attempt to increase the upper temperature limits of metallic sensing elements, many alloys have been tested and used. Table 4.3.5-1 lists the chemical elements used in the design of strain gage sensing elements. Using the elements listed in Table 4.3.5-1, the William J. Bean Company of Detroit, Michigan ran tests on 15 strain gage alloys.[31] The alloys selected were vacuum melted and samples were reduced to fine wire and foil. The selected alloys were classified as nickel-base, iron-base, cobalt-base, platinum-copper, platinum-nickel, and platinum-tungsten. Tables 4.3.5-2 through

4.3.5-7 list the properties of the strain gage alloys established by the tests conducted at the W. J. Bean Company.

All "super alloys" tested (see Table 4.3.5-2) contained significant amounts of nickel and chromium and exhibited solid solution phase changes below 1200F. A solid solution phase change results in an anomaly of the resistance versus temperature curve and yields an unsatisfactory alloy for high temperature strain gage usage.

The test results indicate that platinum nickel and platinum-tungsten alloys have the best stability at high temperatures with the platinum-tungsten alloys exhibiting the least apparent strain. Figure 4.3.5-1 illustrates the effect of temperature on some of the available high temperature strain gages. A review of Figure 4.3.5-1 shows that the platinum-tungsten half bridge gage exhibits the least apparent strain at temperature above 700 F.

4.3.5.1 Sensing Element Forms

Metallic strain gages are formed from small diameter wire or etched from thin sheets of foil. Each type has advantages and disadvantages which should be considered in high temperature applications. Strain gages fabricated using wire sensing elements utilize a small area on the test specimen, thereby reducing the leakage currents which may occur at high temperatures. Foil sensing elements have a relatively large ratio of surface to cross sectional area and exhibits greater stability during long-time period under extreme temperature conditions.

4.3.5.2 Sensing Element Configuration

A major consideration in resistance strain gage design is the sensing element configuration. The most common configuration used in high temperature applications is shaped to measure uniaxial strain. The sensing elements are long and narrow to place the greatest amount of strain sensing material in the direction of the strain being measured. Sensing elements are also designed to measure biaxial and complex multi-directional strain fields. However these configurations are not generally used in high temperature environments.

4.3.6 Methods of Attachments

The method of strain gage attachment is dependent upon the type gage being used, the anticipated environment, and the material on which the gage is to be attached. Table 4.3.6-1 shows the cements available for strain gage attachments. The table lists the cements and their installation properties. A review of Table 4.3.6-1 shows that ceramic cements and aluminum oxide are recommended for attachment of strain gages when the operating temperatures are greater than 700 F.

4.3.6.1 Ceramic Cements

Ceramic cements usually consisting of an oxide or phosphate mixed with a mild acid base are used to attach strain gages for high temperature applications. The cement is first applied to the test specimen to form an insulator

Table 4.3.5-1. Elements for Design of Strain Gages

ELEMENT	ATOMIC NUMBER	MELTING POINT F	RESISTIVITY Ω/CMF	TEMPERATURE COEFFICIENT $\mu\Omega/\Omega$/F	THERMAL EXPANSION /F	MODULUS OF ELASTICITY 10^6 LB/IN^2	OXIDATION TEMPERATURE
AL	13	1220	16	2400	12.9	10	400
Ti	22	3270	300	3000	4.8	15	500
Cr	24	3350	78	1700	4.0	36	800
Mn	25	2268	260	110-180	12.7	2[illegible]	70
Fe	26	2795	60	3400	6.4	29	600
Co	27	2715	38	3700	6.8	30	575
Ni	28	2650	50	2700	7.3	30	1100
Cu	29	1981	11	22	9.2	16	600
Mo	42	4730	30	1800	2.7	50	400
Pd	46	2831	60	1800	6.4	17	1300
W	74	6120	33	2500	[illegible]4	53	300
Pt	78	3224	59	1700	4.9	24	2200

Space Division
North American Rockwell

Table 4.3.5-2. Nickel Based Alloys (Super Alloys)

ALLOY	Ω/CMF @ 100 F	GAGE FACTOR	% ΔR @ 1100 F	% ΔR/100 F	$\mu\Omega/\Omega$/ F	APPARENT $\mu\varepsilon$/ F	NOTES
Nichrome V 80 Ni 20 Cr	650	2.1	4.0	0.4	40	19	Not Stable
Inconel 102 67 Ni 15 Cr 8 Fe 3 Mo 3 W 3 Cd	662-771	2.2	3.2 - 3.6	0.32 - 0.36	32 - 36	15 - 16	Not Stable
Hastelloy N 67 Ni 17 Mo 7 Cr 5 Fe	606-755	2.3	4.0	0.4	40	17	Not Stable
Rene 41	710-816	2.3	1.5 - 4.5	0.15 - 0.45	15 - 45	7 - 20	Not Stable

Table 4.3.5-3. Iron Based Alloys

ALLOY	Ω /CMF @ 100 F	GAGE FACTOR	%ΔR @1100 F	%ΔR/100F	μΩ/Ω /F	APPARENT $\mu\epsilon$/F	NOTES
N-155 30 Fe 21 Cr 20 Ni 20 Co	591-625	2.4	20.5	2.05	205	85	Not Stable

Table 4.3.5-4. Cobalt Based Alloys

ALLOY	Ω /CMF @ 100 F	GAGE FACTOR	%ΔP @ 1100 F	%ΔR/100 F	μΩ/Ω /F	APPARENT $\mu\epsilon$/F	NOTES
L-816 44 Co 20 Ni 20 Cr 4 Mo 4 W 3 Fe	555-610	2.0	13.5 - 155	1.35 - 1.55	135-155	65-75	Not Stable

Table 4.3.5-4. Alloys of Platinum - Copper

ALLOY	Ω/CMF @ 100 F	GAGE FACTOR	%ΔR @ 1100 F	%ΔR/100 F	$\mu\Omega/\Omega$/F	APPARENT $\mu\epsilon$/F	NOTES
80 Pt 20 Cu	220-340	2.0	25	2.5	250	125	Not Stable
80 Pt 15 Cu 5 Ni	440-444	2.1	15	1.5	150	71	Same Stability above 1000 F
80 Pt 15 Cu 5 W	Not workable	Not Workable	5	0.5	50	Not Workable	Not Stable
90 Pt 8 Cu 2 W	320-344	2.4	20	2.0	200	83	Same Stability above 1000 F
90 Pt 5 Cu 5 W	Not workable	Not Workable	22	2.2	220	Not Workable	Unstable above 1000 F

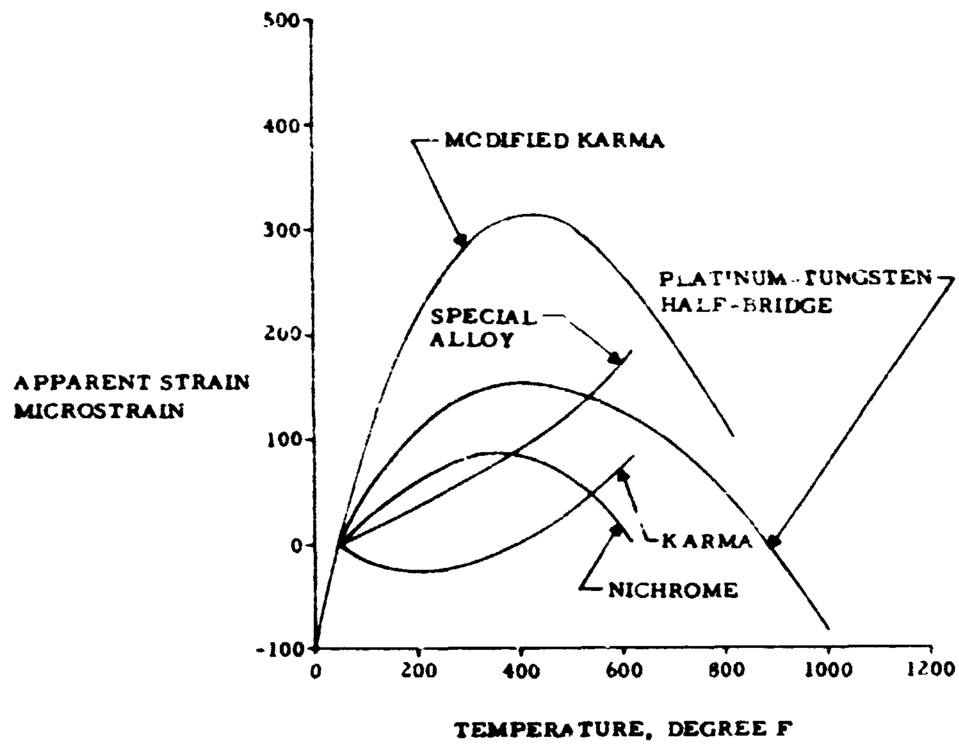
Space Division
North American Rockwell

Table 4.3.5-5. Alloys of Platinum - Nickel

ALLOY	Ω/CMF @ ?00 F	GAGE FACTOR	%ΔR @ 1100 F	%ΔR/100 F	μΩ/Ω/F	APPARENT με/F	NOTES
90 Pt 10 Ni	192	4.2	63	6.3	630	150	Good Stability to 1400 F
90 Pt 8 Ni 2 W	188	4.2	68	6.8	680	162	Good Stability to 1400 F
90 Pt 8 Ni 2 Cr	228	4.1	44	4.4	440	107	Good Stability to 1400 F
90 Pt 5 Ni [illegible]	Not Workable	Not Workable	170	17.0	1700	Not Workable	Erratic above 700 F
80 Pt 5 Ni 15 Cr	440-4?6	2.1	15	1.5	150	?	Unstable above 1000 F

Table 4.3 5-6. Alloys of Platinum - Tungsten

ALLOY	Ω/CMF @ 100 F	GAGE FACTOR	ΔR @ 1100 F	%ΔR/100 F	$\mu\Omega/\Omega$/F	APPARENT $\mu\epsilon$/F	NOTES
92 Pt 6 W	330-355	5.3	21	2.1	210	40	Good Stability to 1400 F
90 Pt 2 W 8 Cu	320-344	2.4	20	2.0	200	83	Not Stable above 1000 F
90 Pt 2 W 8 Ni	188-210	4.2	68	6.8	680	162	Good Stability to 1400 F



[32]
FIGURE 4.3.5-1 APPARENT STRAIN OF AVAILABLE GAGES

Table 4.3.6-1. Strain Gage Cements

TYPE	GAGE CARRIER COMPATIBILITY	MINIMUM CURE TIME F	SAFE TEMP RANGE F	MAX TEMP F	HANDLING CHARACTERISTICS
Nitrocellulose	Thin Paper Base	10 hr @ RT 2 hr @ 120	-100 +180	-320 +200	Single Part Solvent Release
Nitrocellulose	Std Paper	48 hr @ RT 12 hr @ 120	-100 +150	-320 +200	Single Part Solvent Release
Cyanoacrylate	All	0	-100 +150	-320 +200	Use of Catalyst Suggested
Room Temp Epoxy	All	2 to 16 hrs at RT	-320 +150	-452 +300	Two-Part System Must be Mixed
Medium Temp. Epoxy	All Except Paper	2 hr at 350	-452 +400	-452 +500	Single Part System
High Temp Epoxy-Filled	High Temp Glass Reinforced	6 hr at 250 or 2 hr at 350	-452 +400	-452 +650	Usual T -Part System
High Temp Epoxy-Unfilled	Cast Film and High Temp Glass	1 hr at 225	-452 +600	-452 +650	Solvent Thinned Two or More Part Systems
High Temp Polyimide	High Temp Glass Reinforced	2-1/2 hr at 500	-452 +750	-452 +800	Single Part System
Phenolic	High Temp Glass Reinforced	6 hr at 300	-320 +300	-452 +500	Single Part Systems
Ceramic	Strippable or Removable	1-6 hr at 600	-452 +1000	-452 +1250	Single or Two-Part Systems
Aluminum Oxide	Removable Frame	0	-452 +1500	-452 +1600	Flame Spray

for the gage grid. The grid is transferred from its carrier to this precoat and held in position by applying an additional coat of cement. Curing at 600 F produces a hard, porous coat which is serviceable over a temperature range of -452 F to 1000 F.

4.3.6.2 Rokide Process

The Rokide process is patented by the Norton Company, Refactories Division, Worcester, Massachusetts. In operation, a ceramic rod is fed into an oxy-acetylene flame spray gun. The operator holds the spray gun with the nozzle approximately 15 inches away from the gage. The gage is held in position by pressure sensitive teflon tape. Sufficient "Rokide" (aluminum oxide) is sprayed on the gage to tack it in place. The teflon tape is then removed and the installation is sprayed, in the direction of the gage grid, until all grid and lead areas are covered. With sufficient practice and a little care, an excellent gage installation can be made. However, the Rokide installation process can affect the heat treatment of some gage filament alloys.[32] This will cause excessive hysteresis in apparent strain versus temperature during temperature cycling of the installed gage.

Tests have been conducted to determine the insulation resistance of Rokide installation with respect to temperature.[34] An insulation resistance change of from more than 10,000 megohms at room temperature to 100 megohms at 900 F has been noted. A resistance change of this magnitude will cause a change of approximately one microstrain in apparent strain for a platinum alloy gage. This error is not significant when compared to the total apparent strain.

The Rokide process has the advantage of producing a high purity aluminum oxide application in less than five minutes. The inorganic installation will not contaminate deep space environments, minimizes explosive hazards in cryogenic applications, and is highly resistance to nuclear radiation.

4.3.6.3 Welded Gages

Another method of installing high temperature strain measurements is by use of weldable strain gages. The installation of strain gages by welding has the following advantages:

a. A proper weldment forms a 100% transmission of strain.

b. Welding eliminates the complicated bonding agents and high temperature adhesives required to attach other types of gages.

c. There is no specially skilled personnel required or time delays involved in curing and baking. An operator experienced in using an ordinary low-energy capacitive spot welder is all that is required.

There is limitation of only being able to use this method of attachment for strain measurements on metal structures.

Tests have been conducted to determine if the spot welding of strain gages to titanium reduces the fatigue life of the metal.[34] The results of the tests indicate that the maximum stress level was decreased by a factor of 6 when

subjected to 1,000,000 stress cycles. Similar tests have been conducted at room temperature and 1500 F on Inconel-X and Rene 41. The fatigue life was decreased for both the room temperature and the 1500 F tests with welded gage attached. There was also a significant difference between the room and elevated temperature results. The test results showed that welded gages should not be used in applications where a large number of stress cycles are anticipated.

4.3.7 High Temperature Strain Gage Installation

Because of strain gage temperature limitations, care must be taken in choosing locations for the installation of strain-gage instrumentation. Ideally, the gages should be located on inner structure where temperature changes are minimized, causing small variations in apparent strain and gage factors. Even in ideal locations, thermal stresses can significantly affect strain gage output. Realistically, the structure that requires strain gage instrumentation is usually in areas where the temperature is approaching the upper limits of existing gages. The following are some of the installation techniques that will help minimize thermal errors:

a. Locate gages such that each bridge is in close relationship to reduce temperature gradient errors. A 100 microstrain error could equal the average mechanical strain in stiff structures.

b. The lengths of the inner bridge wires should be equal to match their resistances and reduce drift due to lead wire resistance changes with heating.

c. The inner bridge wires and lead wires should be joined using the appropriate joining techniques. Silver brazing and welding are the methods to be used for high temperature applications.

d. The bridge wiring should be routed in such a way that there is no excessive stress on the wires

e. Bridge wiring should be terminated in connectors in which there is no thermal gradient.

f. Each wire bundle should be wrapped with foil to protect the wires from radiant heat.

g. Gages must be well insulated from electrical ground, with a leakage resistance of 1000 megohms or more measured with 50 volts dc applied from the gage to the structure. Leakage resistance will diminish an average of 20 megohms for each 100 F above 500 F.

4.3.7.1 Lead Wire System

Another important consideration in strain gage installation is the lead wire system. The lead wire network must be capable of transmitting electrical signals from the strain gage to the monitoring device with the same accuracy and reliability as the gage itself. The lead wire system is made up of wire

conductor, wire insulation and interconnecting terminals. Table 4.3.7.1-1 lists the lead wire conductor materials available for high temperature applications. The table shows that nickel-chromium alloys such as nichrome or Karma should be used for temperatures up to 1700 F. However, the high resistivity of these alloys limit their use to short lengths at the higher limits of operating temperatures. These nickel-chromium alloys should not be used in place of the clad copper conductors within the temperature limits of the copper materials. Table 4.3.7.1-2 lists lead wire insulations and their temperature ranges. When the temperature range of the strain gage installation is above the temperature limits of organic materials, the lead wires should be insulated with glass impregnated silicone or glass sleeving. In some high temperature installations, ceramic beads made of high-purity alumina or magnesium oxide are used for lead wire insulation.

Stand-off terminals that can be welded or mechanically fastened to the structure should be used for high-temperature installation. The terminal feed-through is usually made of nickel-plated stainless steel which is insulated from the stand-off by teflon, glass, or high-purity alumina. The strain gage leads are joined to the high temperature terminals by welding.

4.3.8 High Temperature Resistance Strain Gage Availability

There are many resistance strain gages on the market today; however, only a relative few advertise the capability of operating at 1500 F. Table 4.3.8-1 lists high-temperature strain gages available and their properties. The upper temperature limit of these metallic element gages is a function of the stability of the element alloys. As metallurgical advancements are made in element alloys, the temperature upper limit should increase.

4.3.9 Conclusions

The currently available resistance strain gages can be used to measure loads in high-temperature environment. However, the installations should be evaluated in a laboratory prior to flight applications to identify necessary corrections in load measurement analysis. In order to use the currently available resistance strain gages in high-temperature application, broad tolerances in measurement accuracy must be accepted.

4.4 ELECTRICAL CAPACITANCE STRAIN GAGE

Past attempts to develop high temperature strain sensors have concentrated on increasing the upper temperature limits of resistance type strain gages. These attempts have been defeated due to the performance characteristics of the available alloys. All of the alloys that could be used for strain sensing either have questionable stability because of a phase change which occurs in the 800 F to 1000 F temperature range or produce undesirable outputs at 1500 F. Since 1968 Hughes Aircraft and the Wright Patterson Air Force Flight Dynamics Laboratory have coordinated in the development of a high temperature capacitance strain gage. [15] The purpose of this section of the report is to review the progress of this strain-sensing device and status the current design.

Table 4.3.7.1-1. Strain Gage Lead Material

CONDUCTORS	OPERATING TEMPERATURE (F)	
	STABLE	MAXIMUM
NICKEL-CLAD COPPER	700	1000
STAINLESS STEEL-CLAD COPPER	800	1300
NICKEL-CLAD SILVER	1000	1500
NICHROME & KARMA	700	1700

Table 4.3.7.1-2. Lead Wire Insulation Materials

INSULATION	TEMPERATURE RANGE (F)
NYLON	BELOW -100
VINYL	-100 to 150
POLYETHYLENE	-100 to 200
TEFLONE	-100 to 500
GLASS IMPREGNATED SILICONE	ABOVE 500
GLASS SLEEVING	ABOVE 500

Table 4.3.8-1.

MANUFACTURER	PART NUMBER	TEMPERATURE RANGE DYNAMIC MEAS.	STATIC MEAS.	GAGE FACTOR	GAGE FACTOR CHG. WITH TEMP.	[illegible]
MICRODOT INC. INSTRUMENT DIVISION 220 PASADENA AVE. SOUTH PASADENA, CAL. 91030	SG 425 SERIES	-452F TO +1500 F	-452F TO +650F	NOMINAL 4.0	1% PER 100 F OVER THE COMPENSATED TEMP. RANGE.	[illegible]
[illegible] INC. 60 OAK STREET, HACKENSACK, NEW JERSEY 07601	[illegible] SERIES	-454F TO +700 F	-454F TO +700 F	NOMINAL 3.2	1% PER 100 F	[illegible]
BLH ELECTRONICS, INC. WALTHAM, MASS. 02154	HT-1200	-452 F TO +1500 F	-452F TO +1200 F	NOMINAL 4.0	DATA NOT AVAILABLE	[illegible]
	FSM SERIES	DATA NOT AVAILABLE	-452F TO +1200 F	NOMINAL 3.8	DATA NOT AVAILABLE	[illegible]
WILLIAM T. BEAN INC. 18915 GRAND RIVER AVE. DETROIT, MICH. 48223	[illegible] SERIES	-320F TO +1200 F	-325F TO +1200 F	NOMINAL 3.10 ± 5%	DATA NOT AVAILABLE	[illegible]
MICRO-MEASUREMENTS BOX 306/38905 CHASE ROAD ROMULUS, MICH. 48174	WK SERIES	-452F TO +700 F	-452F TO +700 F	NOMINAL 3.4	DATA NOT AVAILABLE	[illegible]

. Strain Gage Properties

GAGE RESISTANCE	FATIGUE LIFE	TEMPERATURE COMPENSATION	GAGE MATERIAL	ATTACHMENT
115 OHM ±5.0 OHM - EACH ELEMENT	EXCEEDS 10^6 CYCLES AT [illegible]000 MICRO-STRAINS PER INCH	ABOVE +650°F USE AN ACTIVE DUMMY GAGE COMBINATION	PLATINUM TUNGSTEN ALLOY FILAMENT	WELD ON WELDABLE FERROUS OR NON-FERROUS MATERIALS INCLUDING ALUMINUM & MAGNESIUM
120 OHMS ± .2 OHMS 350 OHMS ± .5 OHMS	DATA NOT AVAILABLE	SELF COMPENSATED	300 & [illegible] (KARMA TYP[illegible]	MOUNTED WITH SPECIAL CEMENT FURNISHED WITH GAGES.
120 OHMS ± 2.5 OHMS 350 OHMS ± 5.0 OHMS	DATA NOT AVAILABLE	USE ACTIVE & DUMMY GAGE FOR COMPENSATION	PLATINUM ALLOY (ALLOY 1200)	CERAMIC OR FLAME SPRAY [illegible]NDING (ROKIDE)
500 OHMS ± 8.0 OHMS 120 OHMS ± 5.0 OHMS	DATA NOT AVAILABLE	USE ACTIVE & DUMMY GAGE FOR COMPENSATION	PLATINUM ALLOY (ALLOY 1200)	WELD
120.0 ± 1.0 OHM	A MINIMUM OF 10^6 CYCLES AT ± 1000 MICRO-STRAINS PER INCH	SELF COMPENSATED	STABILIZED DUEL PLATINUM FILAMENT	CERAMIC OR FLAME SPRAY BONDING (ROKIDE)
120 OHMS ± .3% 350 OHM ± .3% 1000 OHM ± .3%	10^5 CYCLES AT ± 3000 MICRO-STRAIN 10^7 CYCLES AT ± [illegible]0 MICRO-STRAIN	SELF COMPENSATED	MODIFIED KARMA	EPOXY CEMENT

4.4.1 Principle of Operation

The use of a capacitance gage to measure strain is not new. It was developed before the advent of the resistance strain gage. However, using capacitance gages to measure strains at high temperatures is new, and special attention must be given to the gage materials and gage configuration.

The basic equation for a parallel plate capacitor is:

$$C = \frac{AK}{3.6\pi X}$$

where C = capacitance, picofarads
A = area of plates, square centimeters
K = dielectric constant of material between plates
X = separation between plates, centimeters

The principle of operation is that variations in dimensions due to strain will result in capacitance changes. The above equation shows that there are two primary variables that can be used in the strain gage design: the area of the plates and the separation between them.

4.4.2 Gage Configuration

The initial design requirements was for a gage capable of operating under a static strain continuously for one hour in a 1500 F temperature environment. Four gage configurations were considered for testing by Hughes Aircraft Company:

a. A saw-tooth plate in which both the distance between the plates and the effective area are changed with strain

b. Parallel-plate capacitor with tongue-and-groove plates

c. Parallel-plate capacitor in an hourglass strain frame

d. Parallel-plate capacitor in a rhombic frame

The design configuration selected for evaluation was the parallel plate gage mounted in a one-inch by one-inch rhombic frame. The gage consisted of a capacitance wafer containing four stainless steel plates and five mica dielectric insulators mounted in the rhombic stress frame. Figure 4.4.2-1 is a sketch of the selected configuration. The stress frame shown in Figure 4.4.2-1 serves the following basic purposes:

a. Applies an initial compression to the capacitance plates

b. Acts as a strain amplifier. By the geometric configuration, a 2 to 1 amplification factor is applied to the specimen strain.

c. Provides for a method of attachment to the test specimen.

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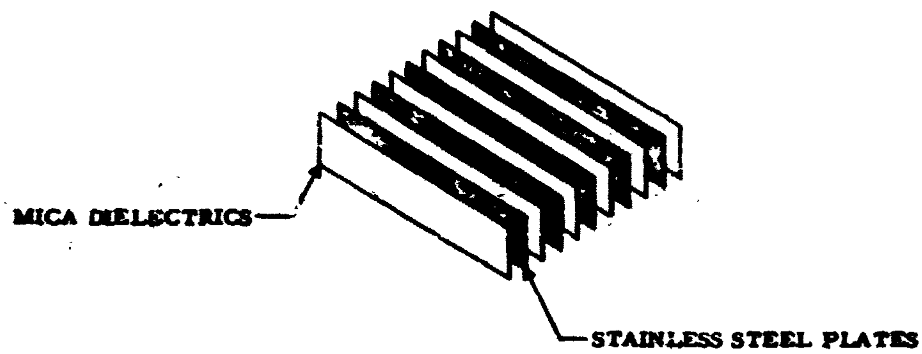

CAPACITOR ELEMENT (EXPLODED VIEW)

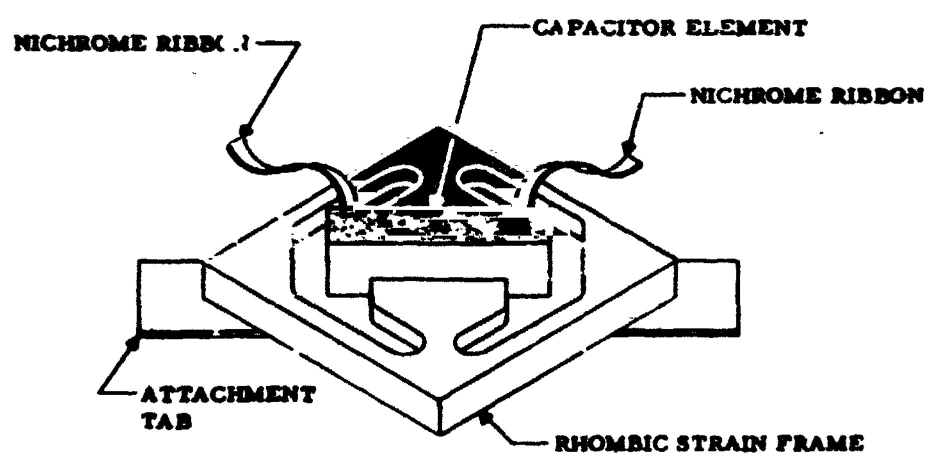

Figure 4.4.2-1 [35] Capacitance Gage with Parallel Plates

The rhombic frame design provides another basic advantage. A review of the parallel plate capacitor equation shows that as the distance X increases, the capacitance C decreases. Conversely, as X decreases C increases. The rhombic frame allows a tension on the gage to decrease the gap between the plates X and therefore increase the capacitance. This not only places the readings in their normal order of tension, increasing and compression decreasing, it also allows for a built-in correction for apparent strain. As the gage is heated, the dielectric constant increases approaching infinity. In order to correct for this effect, it is necessary to separate the plates by a predetermined amount. By proper selection of materials, it is theoretically possible to provide the required apparent strain correction.

4.4.3 Test Results

A total of 15 gages were fabricated and tested on a constant moment beam apparatus at both room temperature and 1500 F. The performance of these gages in the initial tests conducted by Hughes Aircraft Company were very satisfactory. Table 4.4.3-1 is a summary of the gage performance as compared to the target specification requirements. A review of Table 4.4.3-1 shows that the gage performance met most of the specification requirements. The notable exceptions are its gage-to-gage repeatability in gage factor, the effects of temperature on gage factor and apparent strain.

4.4.4 Current Design Status

In 1970 another high-temperature capacitance strain gage development program was undertaken by Hughes Aircraft Company under Air Force Contract F33615-70-C-1181. [36] The program was completed in October 1971. The primary objectives of this program were to expand the temperature range of the previous gage from 1500 F to 2000 F and reduce its size from 1-inch gage length to 0.5-inch gage length. The program consisted of the following:

a. Research of dielectric and metallic components to determine optimum materials.

b. Study of attachment techniques for various structural materials

c. Investigation of cables to withstand the 2000 F temperature.

d. Manufacture of a sufficient number of high-quality gages to permit evaluation.

e. Provide a test plan and procedure for evaluation.

f. Provide adequate testing to determine gage-to-gage and cycle-to-cycle characteristics.

4.4.4.1 Gage Configuration

The previously designed 1500 F gage was a parallel plate capacitor with a variable gap held in a rhombic frame. The gage had a 1-inch gage length and an area of 0.50 square inches. It was required to reduce the gage length to

Table 4.4.3-1. High Temperature Capacitance Strain Gage Performance

ITEM	REQUIREMENT	PERFORMANCE
GAGE LENGTH	< 1 INCH	1 INCH
GAGE CAPACITANCE	10 < C < 100 PICOFARAD	11 < C < 1[illegible] PICOFARAD
GAGE FACTOR	25	~ 25
REPEATABILITY	± 2 PERCENT/100 F	± 5 PERCENT OVERALL
GAGE FACTOR CHANGE WITH TEMP.	± 2 PERCENT/100 F	± 4 PERCENT/100 F
STRAIN LIMIT (1500 F)	± 5000 μ IN/IN	+ 5000, -2000 μ IN/IN
DRIFT RATE	900 μ IN/IN/HR @ 1500 F	100 μ IN/IN/HR @ 1500 F
MIN RESISTANCE TO GROUND	10 MEG Ω	NO CONSEQUENCE
APPARENT STRAIN	5 μ IN/IN/F	5 μ IN/IN/F @ 1500 F
MAXIMUM ZERO SHIFT	50 μ IN/IN	50 μ IN/IN

0.50 inch and the area to 0.125. Many configurations were analyzed including: Parallel plate with variable area/gap, coaxial cones with variable area/gap, rotary parallel plates with variable area and coaxial concentric with variable length. All were housed in rhombic or circular strain frames. Based on evaluation of combinations of sensors and frames, the parallel plate capacitor with a variable gap and rhombic frame was selected as the best configuration for the 0.50-inch gage.

4.4.4.2 Gage Materials

The materials selected for evaluation as potential dielectrics were:

a. Air

b. Mica (phlogopite)

c. Silica

d. Titania (titanium oxide)

e. AD99 (alumina)

f. Glasrock

g. Barium titanate

Glasrock, silica, mica and AD99 were the only materials providing useable results at 2000 F. Of these materials, mica and glasrock appeared to be the the best dielectric. Because of its relative handling ease, mica was chosen as the dielectric material for the 2000 F capacitance strain gage.

4.4.4.3 Attachments Techniques

The attachment of strain gages for measurements in a 2000 F environment is extremely difficult. In many cases the base materials must be coated to prevent oxidation or other chemical reaction from occurring at elevated temperatures which makes bonding difficult. Welding gages sometimes contribute to a secondary fatigue problem at these temperatures.

The attachment techniques investigated were welded, flame sprayed and bonded. The base metals selected for capability tests were super alloy (605), dispersion strengthened material (TD nichrome) and coated refractory (Niobium with sylcor coating). The specimen attachment techniques were developed by using 302 stainless steel ribbon 0.30-inch wide and 0.005-inch thick to simulate the attach tabs on the strain frame.

a. Welded Attachment

For the niobium base material, two techniques were evaluated: first, scraping the sylcor coating from the niobium and and welding the ribbon to the base material; second, coating the sylcor with a flame spray coating of Metco 450 nickel aluminum and then welding to this coating.

All of the welding techniques proved adequate for attaching the capacitance strain gage.

b. Flame Spray Attachment

All flame spray attachments were made using a Metco flame spray gun and Metco spray materials. The most successful technique consisted of spraying a thin precoat of Metco 450 on the base material. Two 3/32-inch holes were punched in the attach tabs which were then taped in place on the precoated material. A coating of 10 to 15 mils thick was then sprayed over the attach tabs, filling the punched holes.

c. Bonded Attachment

The adhesives evaluated for bonded attachments were Sauerizen 29, Ultra Temp 516 and Allen P-1. Tests conducted on these adhesives indicated that Ultra Temp 516 was the best adhesive for the 2000 F usage.

A comparison of the three attachment methods revealed that the flame spray is the strongest. However, welding is the preferred method because of its ease of application. Bonding was only satisfactory with TD-nichrome material.

4.4.4.4 Lead Cable Evaluation

The coaxial cable selected for the 2000 F application was manufactured by the Maser Rex Hi Temp Wire Company of Monrovia, California. It consisted of a 0.020-inch stainless steel conductor insulated with General Electric quartz fiber and shielded with braided 304 stainless steel.

4.4.4.5 Gage Installation

The strain gage is installed in the following manner:

a. Align the attach tabs along the strain axis and spot weld each tab in three equal places.

b. Weld gage leads to signal leads keeping signal leads as short as possible.

c. Weld a gage shield over gage area. This shield eliminates the capacitance effect from conductors located close to the gage and signal leads. The shield is made for 0.020 to 0.050 inch stainless steel and should clear the high temp leads by 0.25 inch.

4.4.4.6 Testing

A total of 25 gages were fabricated for testing. Each gage consisted of a 0.50 inch gage length rhombic stress frame made of TD nickel and a sensing element made of inconel plates separated by a dielectric of phlogopite mica. Twenty of the gages were cured at 1625 F and five gages at 2000 F. The gages were installed on TD nichrome test bars which were then placed in a constant moment fixture, strained to 2500 micro strains and heated to 2000 F.

4.4.4.7 Gage Performance

The gage performance was considered in two parts: gages cured at 1625 F and gages cured at 2000 F.

Performance of the 1625 F cured gages was as follows:

a. Maximum temperature limited to 1750 F.

b. Initial capacitance averaged 8 picofarads which is below the target specification of 10 to 50 picofarads.

c. Gage-to-gage variations were extensive. However, the ability to precalibrate the gages eliminates this as a problem.

d. The strain limit is $^{+5000}_{-2000}$ microstrain at room temperature and $\pm$ 1500 to 2000 microstrain at 1750 F.

e. The apparent strain was within target specification of 5 microstrain per degree F at maximum heating rate.

f. The drift rate was greater than target specification of 300 microstrain at maximum temperature.

g. The zero shift per cycle was better than specification requirements

The gages cured at 2000 F will provide data at temperatures up to 2000 F. However, considerable accuracy is lost. Due to drift and apparent strain, the initial capacitance was more than doubled when the temperature was stabilized at 2000F.

4.4.8 Conclusions

The current capacitance strain gage is a prototype design with a 0.50-inch gage length. It is capable of static strain operation up to 2000 F in the environment of a structural test laboratory using infrared heat lamps as the heat source. At the time of this writing, the gage is not commercially available and has not been considered for airborne applications.

4.5 THERMAL-NULL STRAIN GAGE

The Boeing Company, Seattle, Washington and the NASA Flight Research Center, Edwards, California coordinated in the development and testing of a thermal null strain measuring system capable of operating in a 1500 F thermal environment. [37]

4.5.1 Principle of Operation

The thermal null approach is a relatively new way of measuring mechanical strain at elevated temperatures. The operating principle consists of creating an induced thermal expansion proportional to a mechanical strain. A temperature measurement is made to indicate the amount of thermal expansion which is

then translated into mechanical strain. The operating principle of the thermal null strain gage is best explained by considering the functions of its four basic parts shown in Figure 4.5.1-1.

a. A link or beam to span the portion of the specimen over which the strain is to be measured. The beam can be made of the same material as the specimen, thus eliminating any length difference due to differential thermal expansion. This makes the gage self temperature compensating.

b. A heater to heat the beam such that the resulting thermal expansion can be made equal to the applied strain.

c. A position detector that indicates when the beam length is equal to the span length of the strained specimen.

d. A differential temperature sensor to measure the temperature change between the beam and the test specimen. This indicates the amount of thermal expansion required to restore the beam length to that of the test specimen span.

4.5.1.1 Sequence of Operation

The sequence of operation of a typical thermal null strain gage is as follows:

a. The gage and the test specimen are exposed to an increasing ambient temperature.

b. The span length of the specimen increases due to thermal expansion and the gage beam increases an equal amount thus the delta length change is zero.

c. The specimen is mechanically strained in tension.

d. The position detector senses that the gage beam length is less than specimen span.

e. The heater is energized to thermally expand the gage beam until the position detector indicates that the delta length has returned to zero.

f. The differential temperature sensor measures the change in temperature between the specimen and the gage beam which is proportional to the amount of induced thermal expansion required to equal the applied mechanical strain. The output of the temperature sensor is calibrated directly in terms of mechanical strain.

4.5.1.2 Measuring Compression Loads

To make the gage capable of responding to compression loads, a "bias power" is applied to pre-heat the beam. The position detector is then adjusted to null out the increased length. From this pre-heated condition, the beam will contract by decreasing the heater power. The temperature sensor responds to a decrease in beam temperature to indicate compression strain.

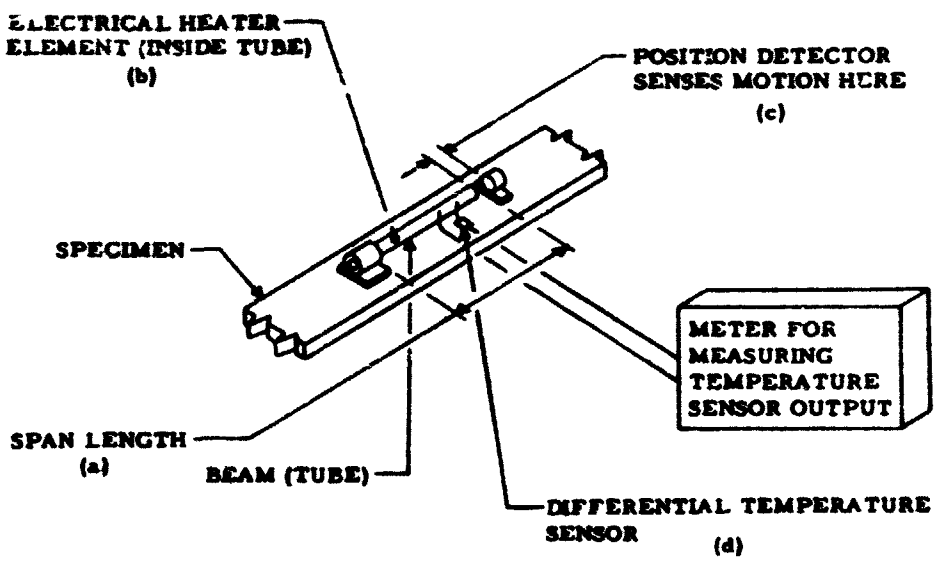

Figure 4.5.1-1[37] Thermal-Null Strain Gage

4.5.2 Strain Gage Configuration

The gage configuration shown in Figure 4.5.1-1 is approximately 1.25 inches long and consists of the following components:

a. The beam or link is made of .040-inch tubing rigidly attached to the test specimen at one end. The other end is free to move in the axial direction.

b. The heater consists of a small-diameter, high-resistance wire, coiled to form a helix and located inside the tube.

c. The position indicator is a differential capacitor consisting of three plates, one of which moves in relation to the other two fixed plates.

d. The temperature sensor consists of a thermopile having alternate thermocouple junctions on the specimen and on tube. The thermopile indicates the temperature change in the tube required to null the position indicator. The voltage generated by the temperature sensor is used directly to indicate the mechanical strain output of the system.

4.5.3 Gage Performance

Fifteen gages were fabricated for testing. Inconel-X, Rene 41, and Haynes 25 were used for gages and load test specimens. Tests were conducted on all three alloys at temperatures up to 1500 F and at mechanical strains of up to 1500 microstrain.

The performance characteristics of the thermal null gage are dependent on the instantaneous thermal expansion of the test specimen and gage beam and the instantaneous response of the thermopile. The gage performance consisted of evaluating the following characteristics:

a. Mechanical strain sensitivity

b. Apparent strain output

c. Mechanical strain sensitivity over the operating temperature.

The test results were very favorable for the mechanical strain sensitivity and apparent strain output. However, the mechanical strain sensitivity as a function of temperature showed a decrease in sensitivity above 750 F. This sensitivity decrease was due to the increases in the thermal expansion coefficient of the tube and specimen. Below 750 F this thermal expansion is cancelled by the thermocouple electro-motive force coefficients.

4.5.4 Conclusions

The thermal null concept provides a technique for reducing errors in high temperature strain measurements. The measurement range of the gage depends on the expansion and contraction limits of the tube. The expansion is limited by the available power to the heater and the contraction is limited by the ambient temperature. At the time of this writing the gage is not commercially available and is limited to evaluation and laboratory use.

4.6 CONCLUSIONS AND RECOMMENDATIONS

Of the three strain sensing devices evaluated, only the capacitance gage is capable of operation in a 1500 F to 2000 F thermal environment. However, this device is still in the prototype design stage and is not commercially available. It has only been evaluated under laboratory conditions and has never been subjected to flight environment. The current designed gage, with a 0.50-inch gage length, is small enough for airborne application if it is capable of surviving the acoustic and dynamic environments associated with high-speed flight.

The thermal-null gage is also in the prototype design stage. The concept and gage performance has been proven in laboratory tests in a 1500 F thermal environment. The current design has not been tested for airborne applications. However, test results to date indicate that the principle could be developed into an airborne gage.

Electrical resistance strain gages are currently available that will measure static strain in a 900 F environment and dynamic strain in a 1500 F environment. The strain gage element alloys presently available have questionable stability in the 800 F to 1000 F temperature range or produce undesirable outputs at 1500 F.

Until such a time that capacitance strain gages, or thermal-null strain gages become available, the following is recommended for high-temperature airborne strain measuring applications:

a. Use resistance strain gages having platinum tungsten alloy elements.

b. Use active and dummy gages with compensating resistors for temperature compensation.

c. Use weldable gages if possible. If welding is not possible, use flame spray for attaching gages.

d. If the gages are to be used in a thermal environment above 800 F, the installation should be evaluated in a laboratory prior to actual flight testing. This will verify proper selection of the gage and identify the magnitude of thermally induced errors which will aid in interpreting the accuracy of flight data.

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